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Hong et al.

(10) **Patent No.: US 9,233,540 B2**
(45) **Date of Patent: Jan. 12, 2016**

(54) **PRINTING SYSTEM, PRINTING APPARATUSES, AND METHODS OF FORMING NOZZLES OF PRINTING APPARATUSES**

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(73) Assignee: **SAMSUNG ELECTRONICS CO., LTD.**, Gyeonggi-Do (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/519,736**

(22) Filed: **Oct. 21, 2014**

(65) **Prior Publication Data**

US 2015/0035911 A1 Feb. 5, 2015

Related U.S. Application Data

(62) Division of application No. 13/604,269, filed on Sep. 5, 2012, now Pat. No. 8,898,902.

(30) **Foreign Application Priority Data**

Sep. 8, 2011 (KR) 10-2011-0091319

(51) **Int. Cl.**
B41J 2/165 (2006.01)
B41J 2/14 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***B41J 2/1433*** (2013.01); ***B41J 2/06*** (2013.01); ***B41J 2/14201*** (2013.01); ***B41J 2/14233*** (2013.01); ***B41J 2/14314*** (2013.01); ***B41J 2/16*** (2013.01); ***B41J 2/161*** (2013.01); ***B41J 2/162*** (2013.01); ***B41J 2/1623*** (2013.01); ***B41J 2/1629*** (2013.01); ***B41J 2/1631*** (2013.01); ***B41J 2/1632*** (2013.01); *Y10T 29/49401* (2015.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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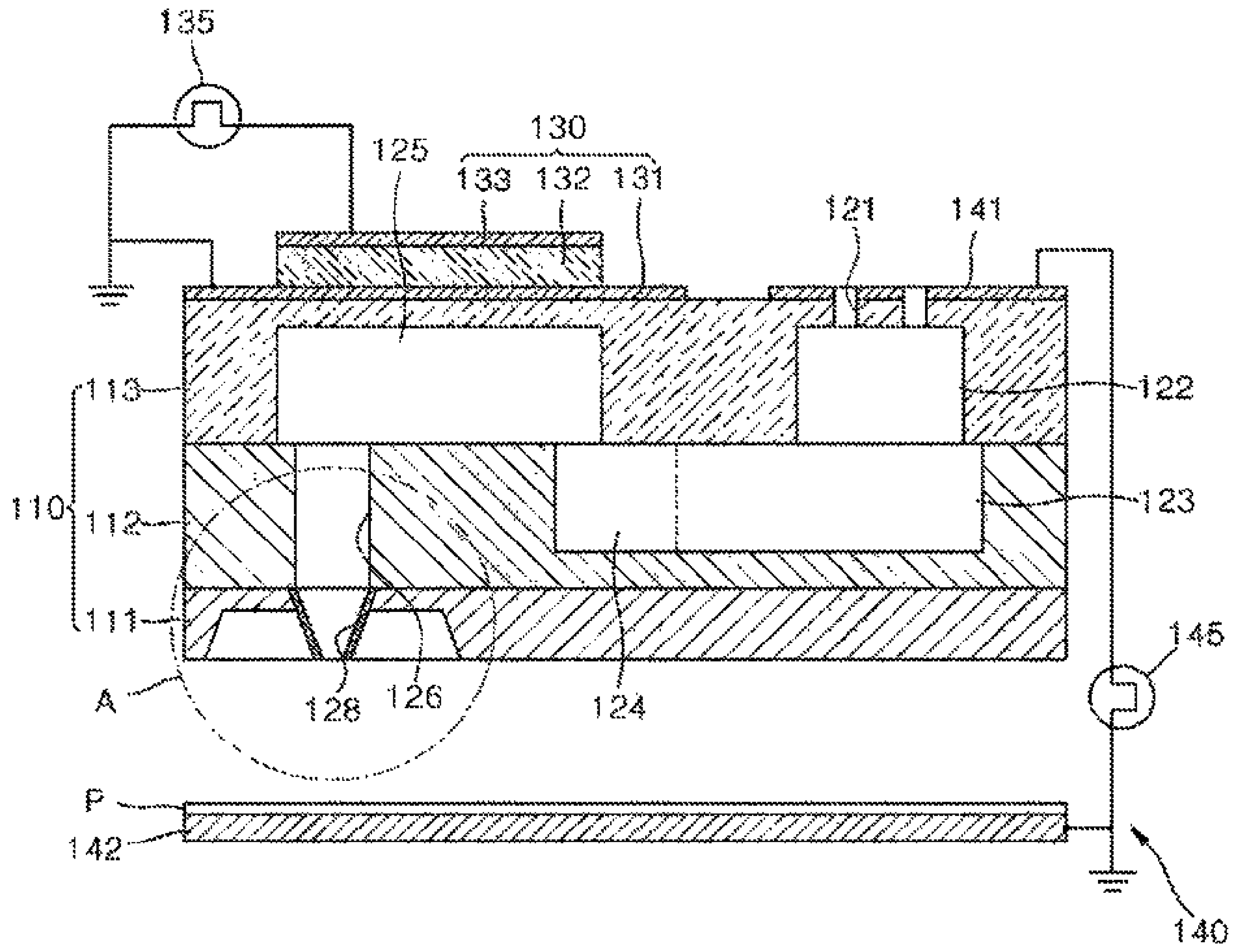
Primary Examiner — Erica Lin
(74) *Attorney, Agent, or Firm* — Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

A printing apparatus includes: a flow channel plate including, a pressure chamber, a nozzle including an outlet through which ink contained in the pressure chamber is ejected, and a trench disposed around the nozzle, and the outlet extending into the trench; a piezoelectric actuator configured to provide a change in pressure to eject the ink contained in the pressure chamber; and an electrostatic actuator configured to provide an electrostatic driving force to the ink contained in the nozzle.

16 Claims, 28 Drawing Sheets



(51) **Int. Cl.**

B41J 2/06	(2006.01)
B41J 2/16	(2006.01)

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WO	WO-03/070381	A1	8/2003

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FIG. 1

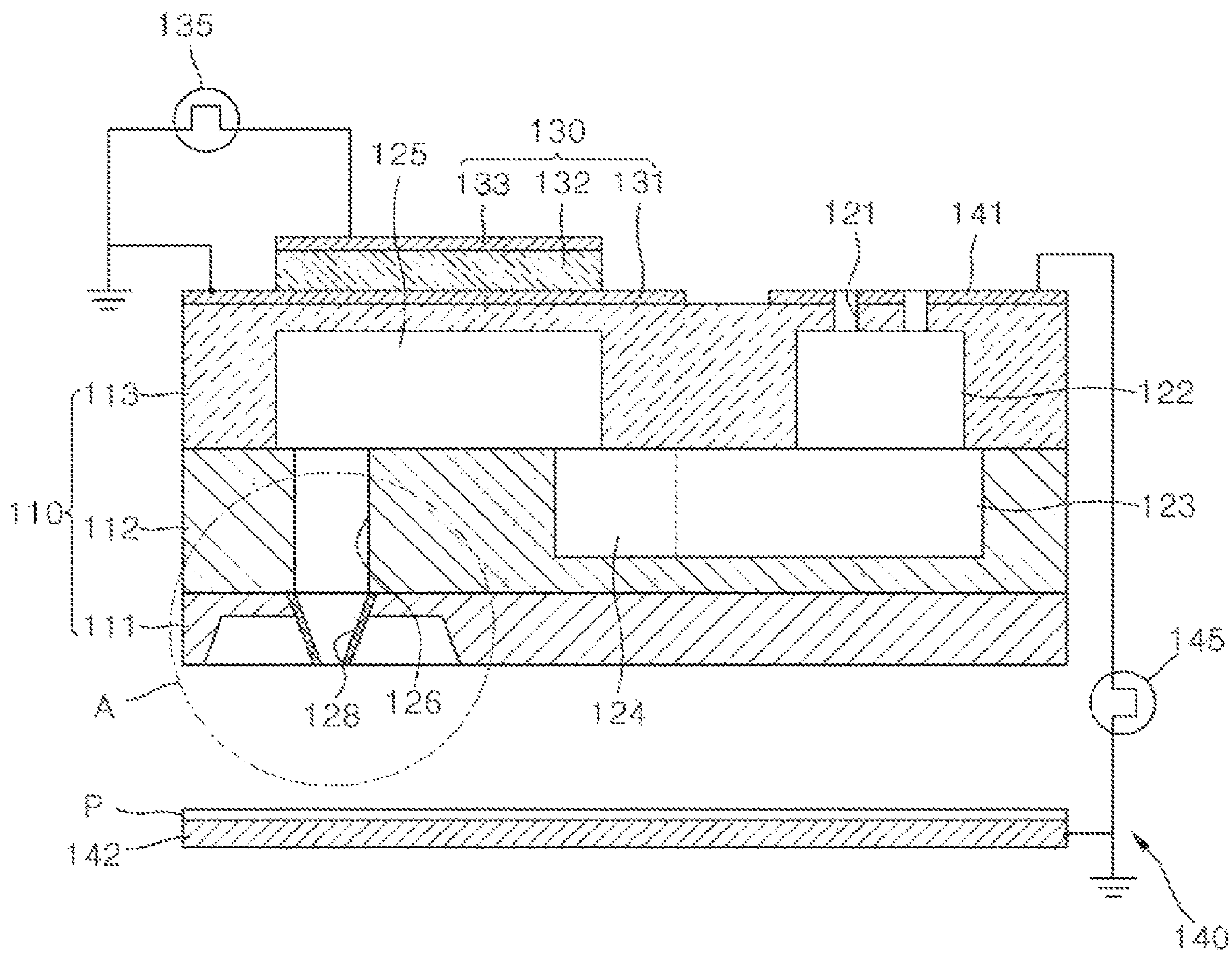

135
130
125
133
132
131
121
141
113
122
110
112
123
111
A
128
126
124
145
P
142
140

FIG. 2

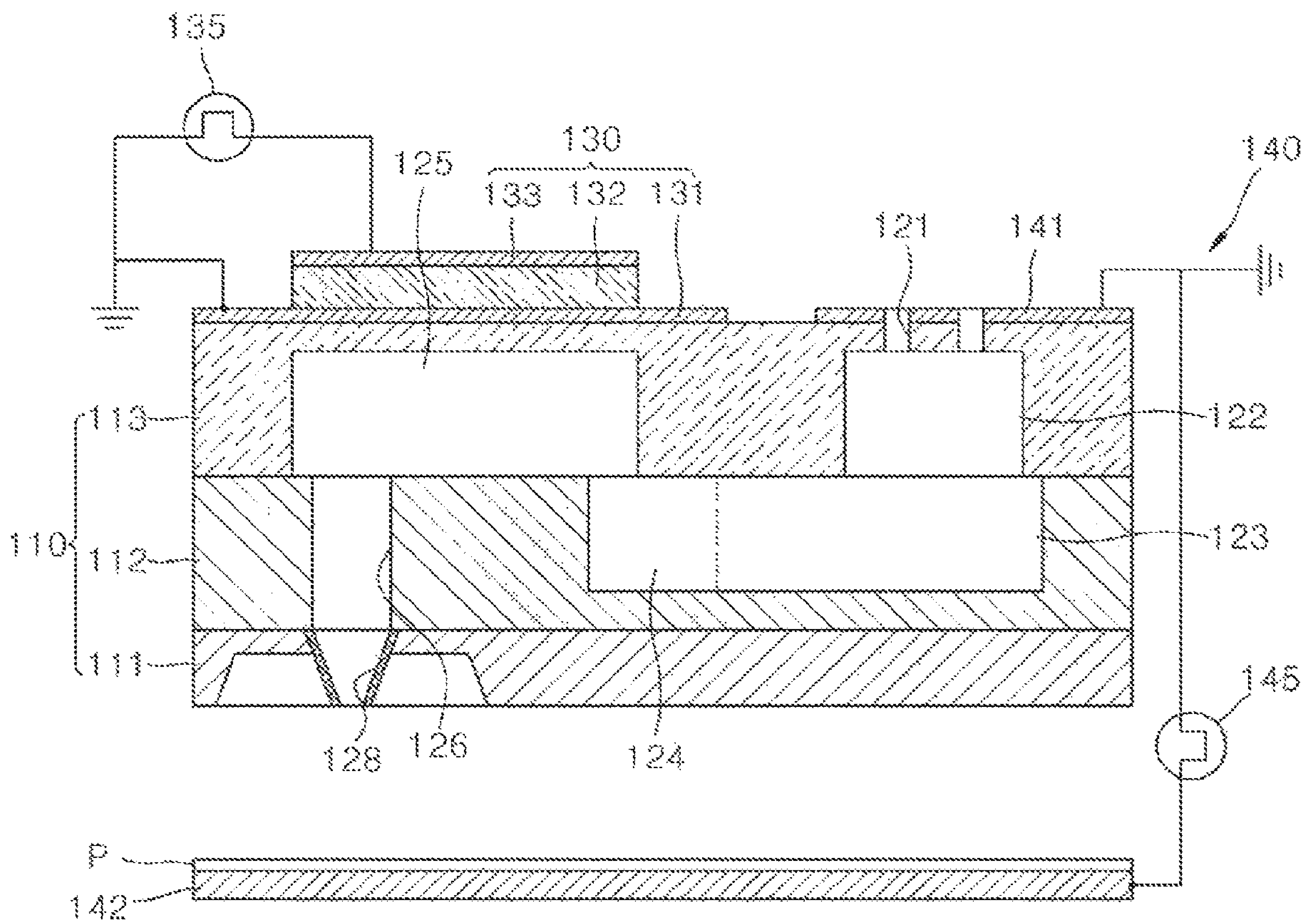

135
130
125
133
132
131
121
141
140
113
122
110
112
123
111
128
126
124
145
P
142

FIG. 3

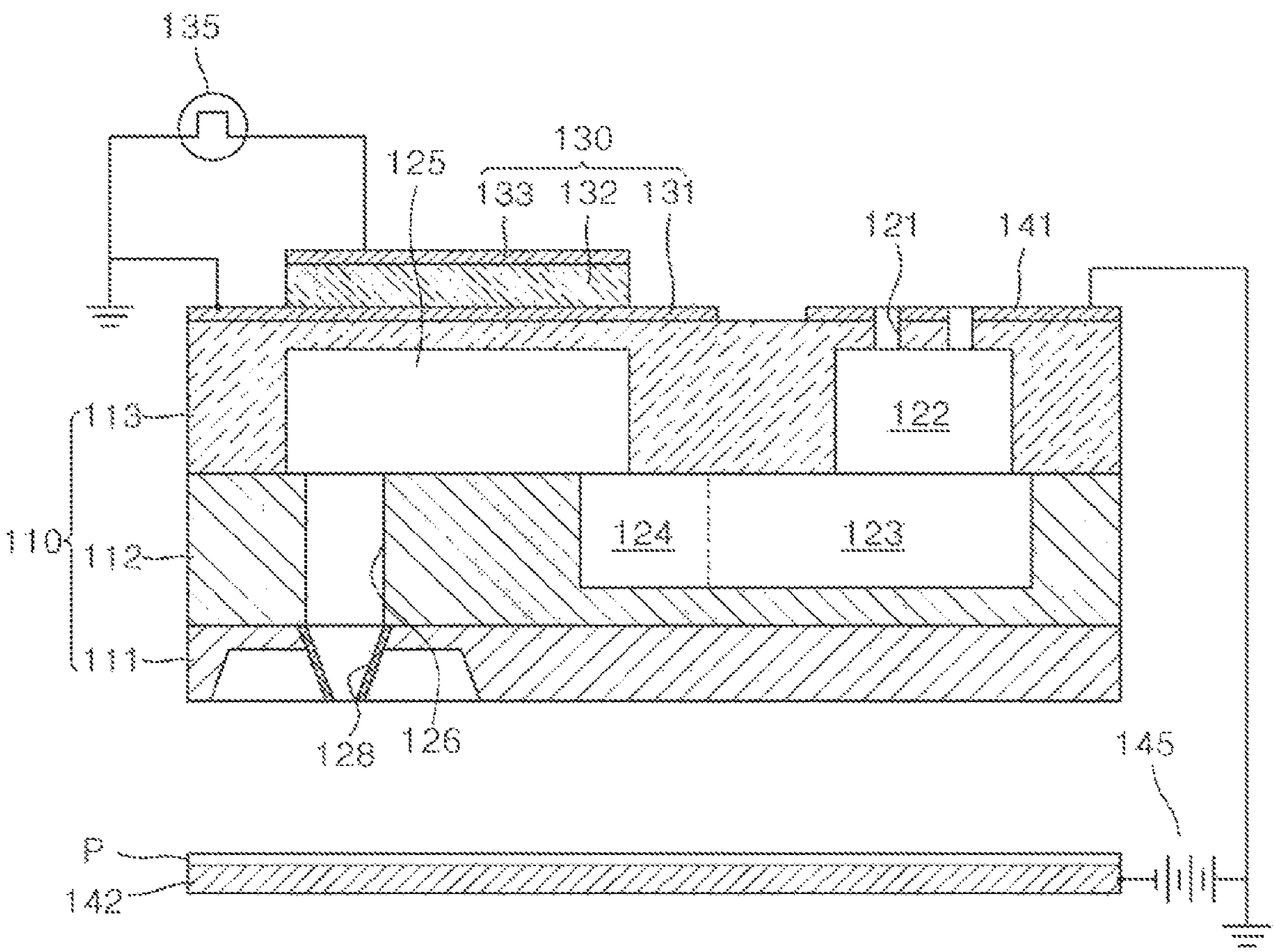
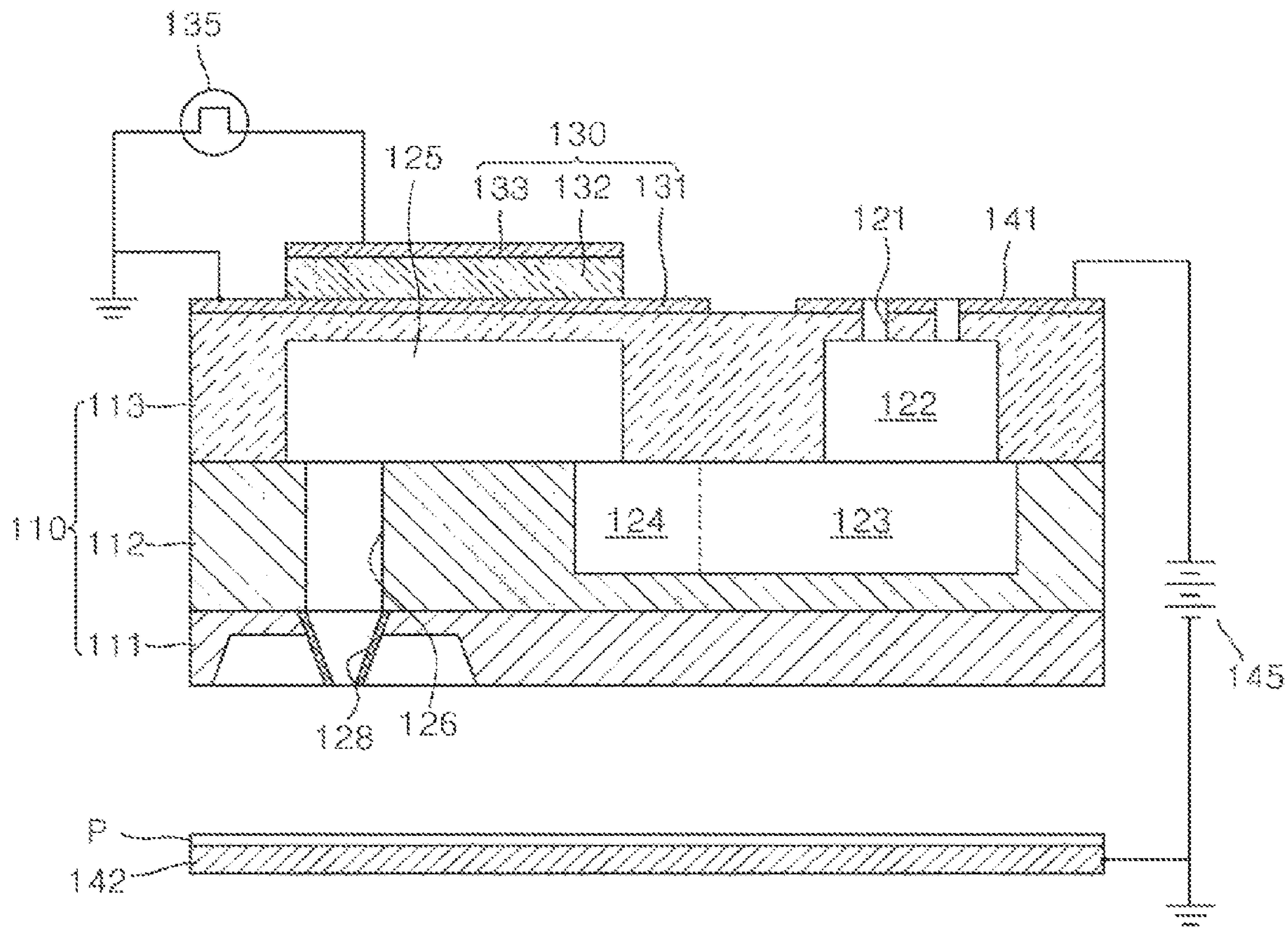

135
130
125
133
132
131
121
141
113
122
110
112
124
123
111
128
126
145
P
142

FIG. 4



135
130
125
133
132
131
121
141
113
122
110
112
124
123
111
145
128
126
P
142

FIG. 5

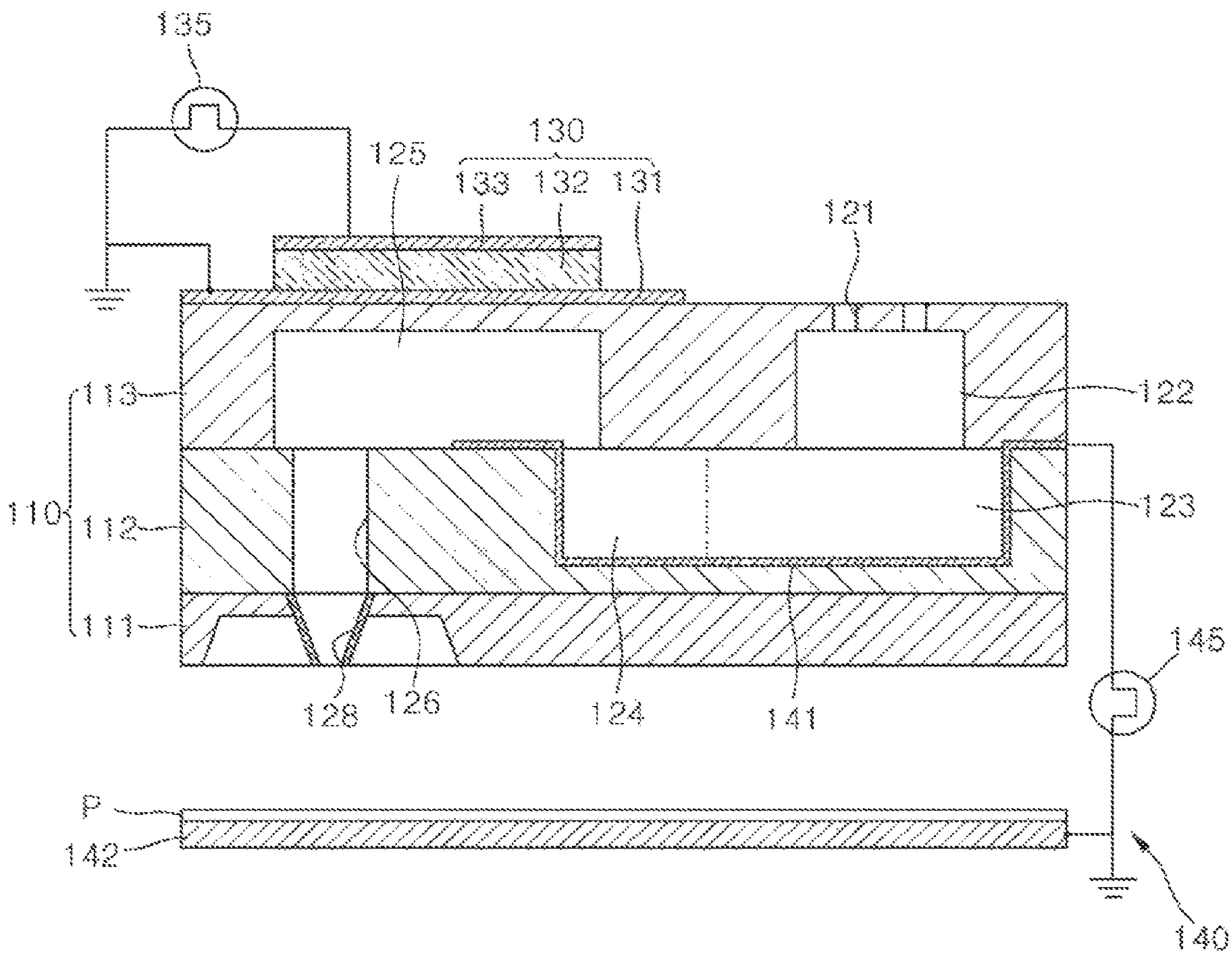

135
130
125
133 132 131
121
122
110
113
112
111
123
145
128
126
124
141
P
142
140

FIG. 6

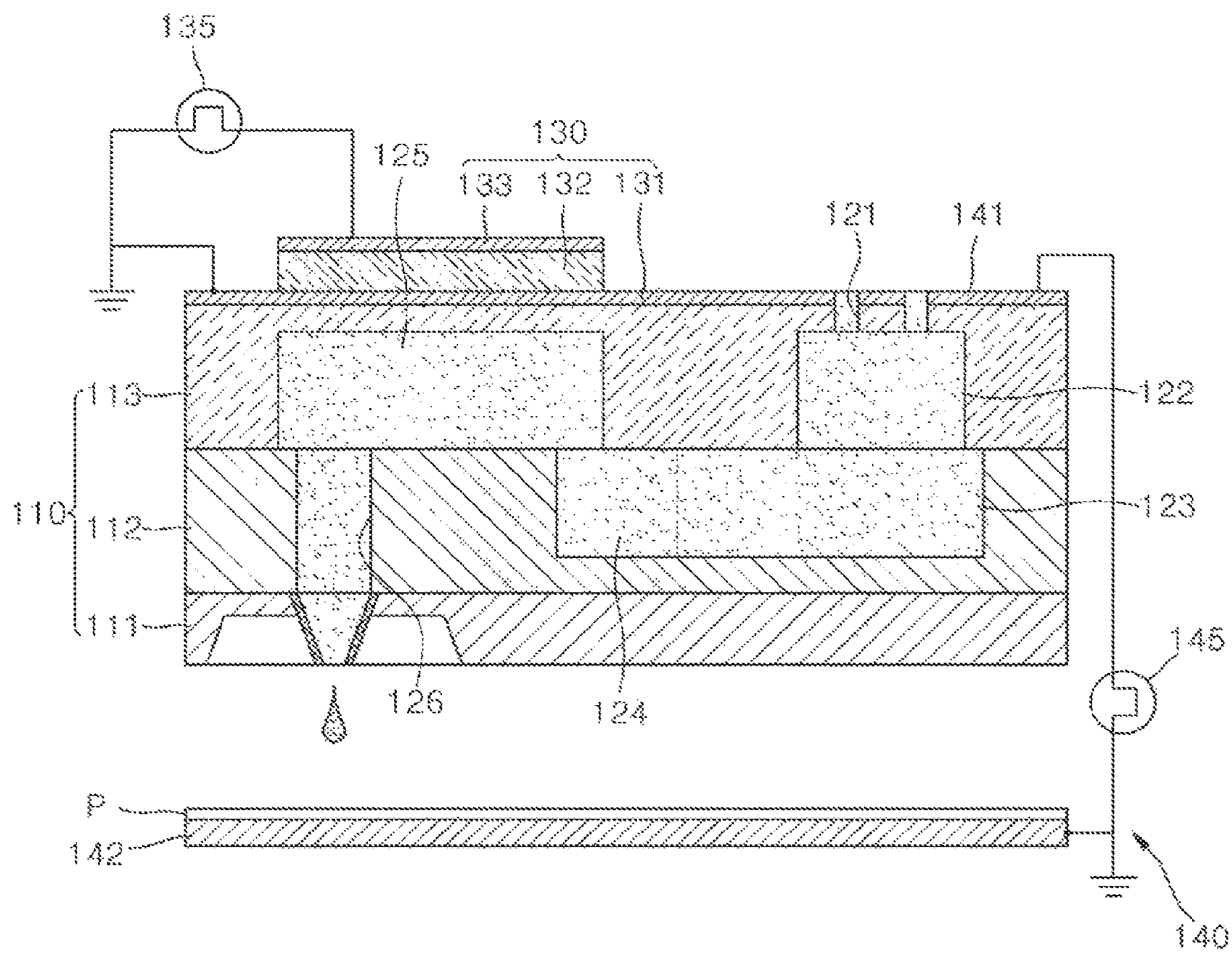

135
130
125
133 132 131
121
141
113
122
110
112
123
111
145
126
124
P
142
140

FIG. 7A

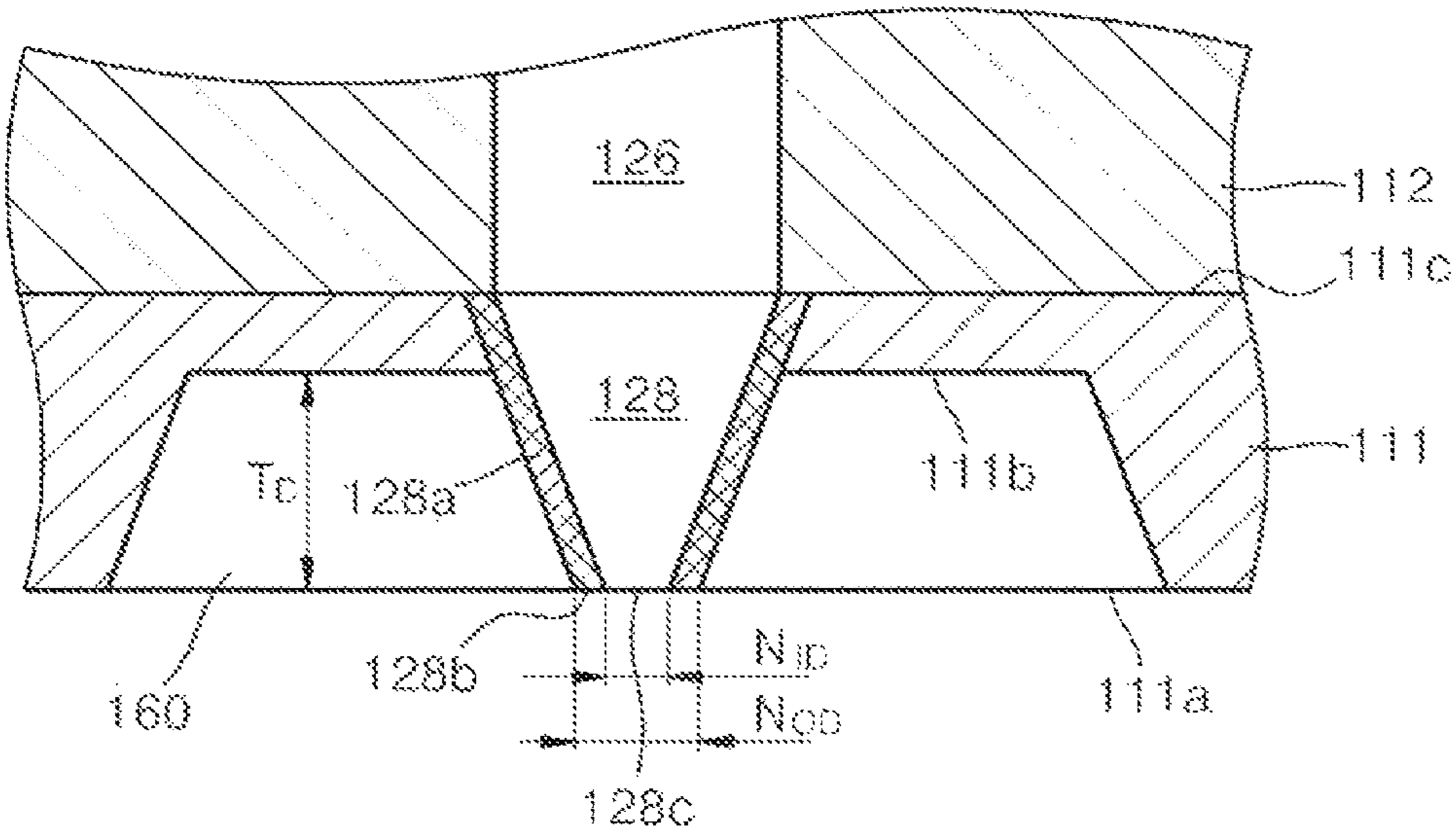

126
112
111c
128
111
111b
Tc
128a
160
128b
N_{ID}
N_{OD}
111a
128c

FIG. 7B

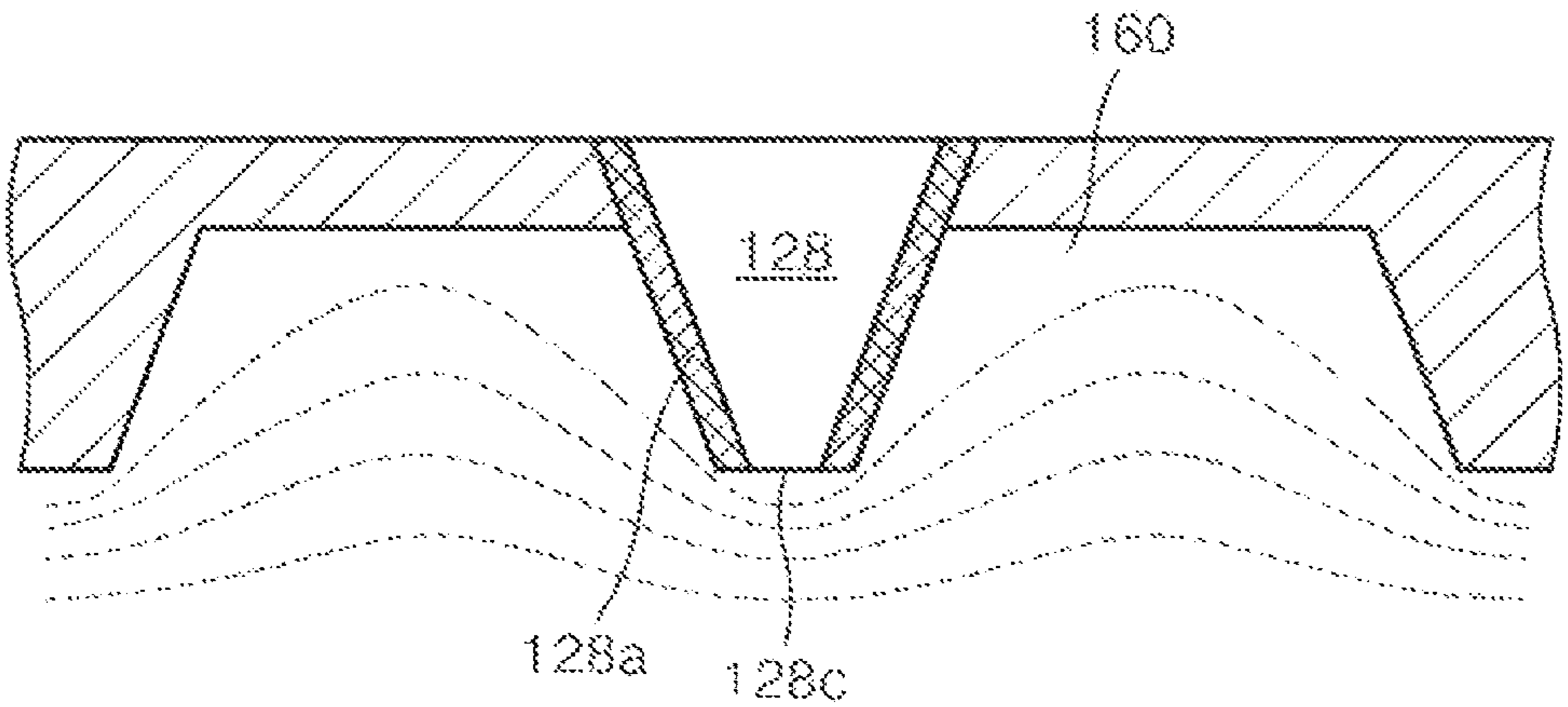

160
128
128a
128c

FIG. 7C

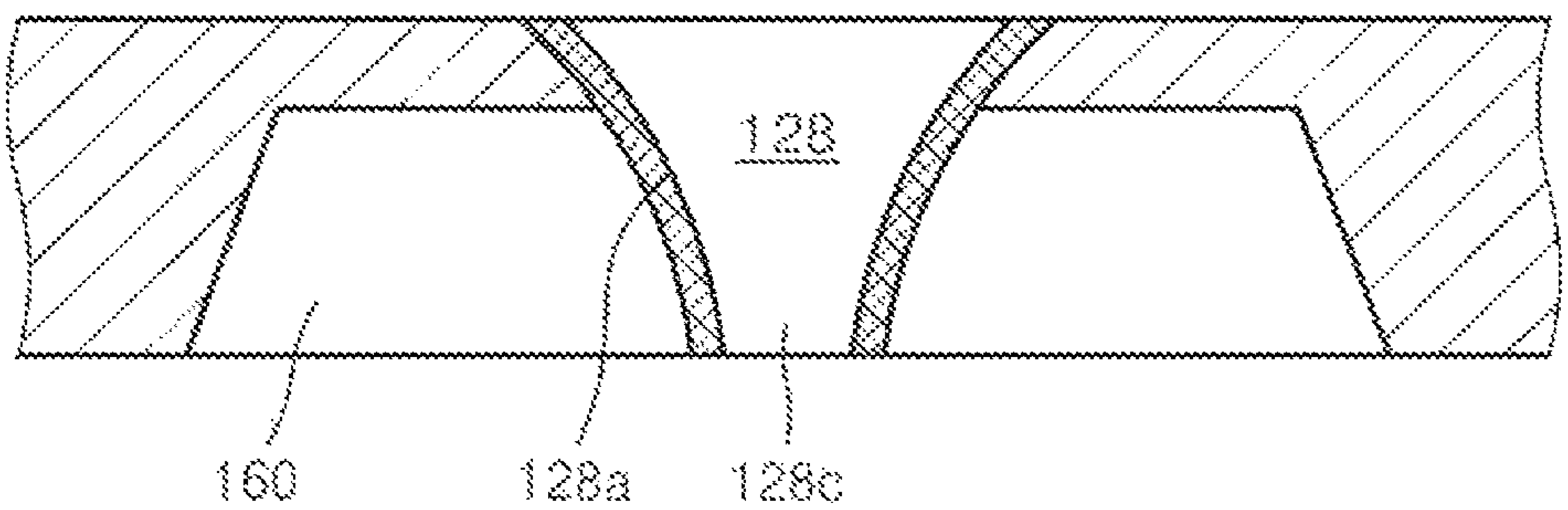


FIG. 7D

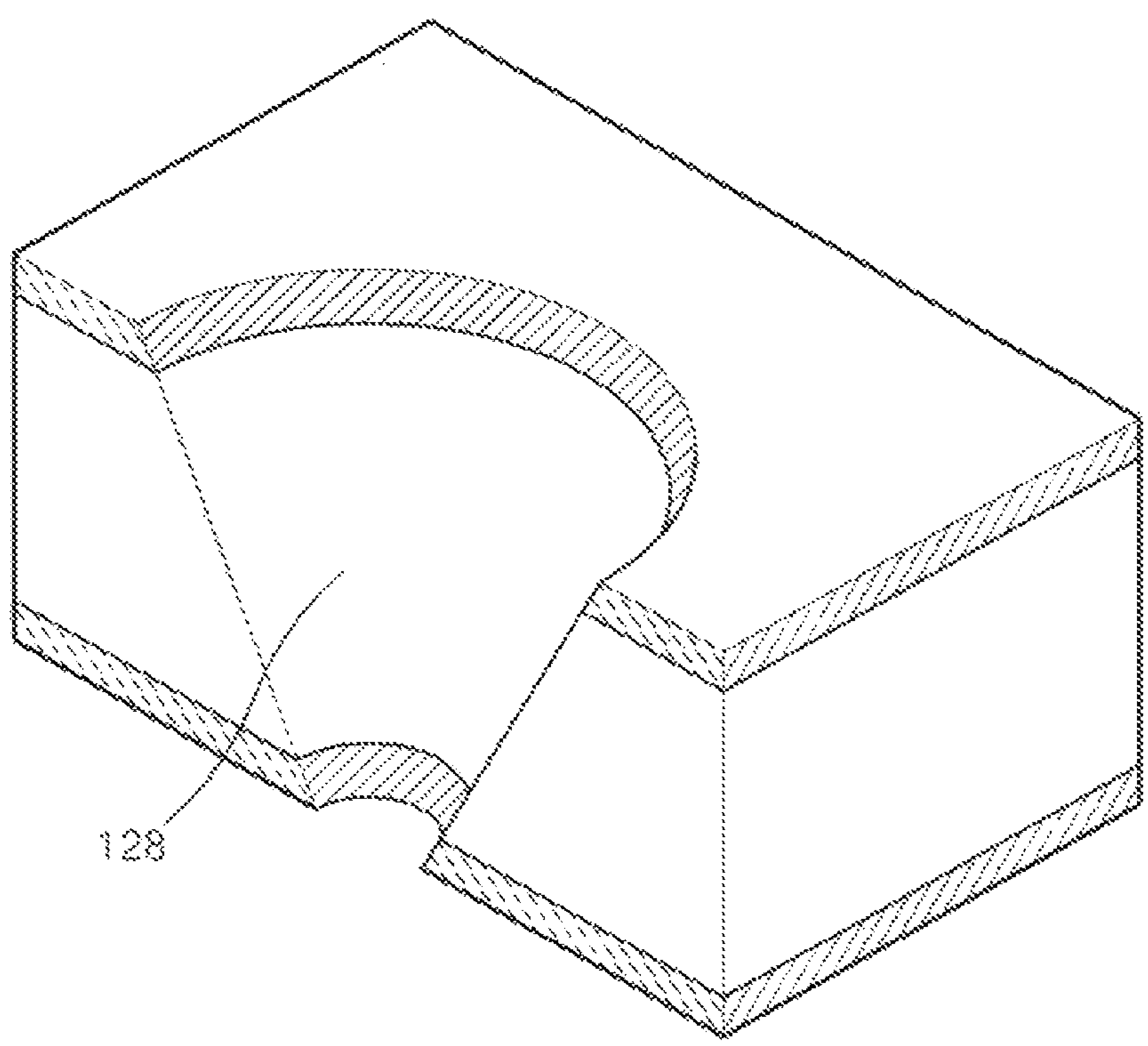


FIG. 7E

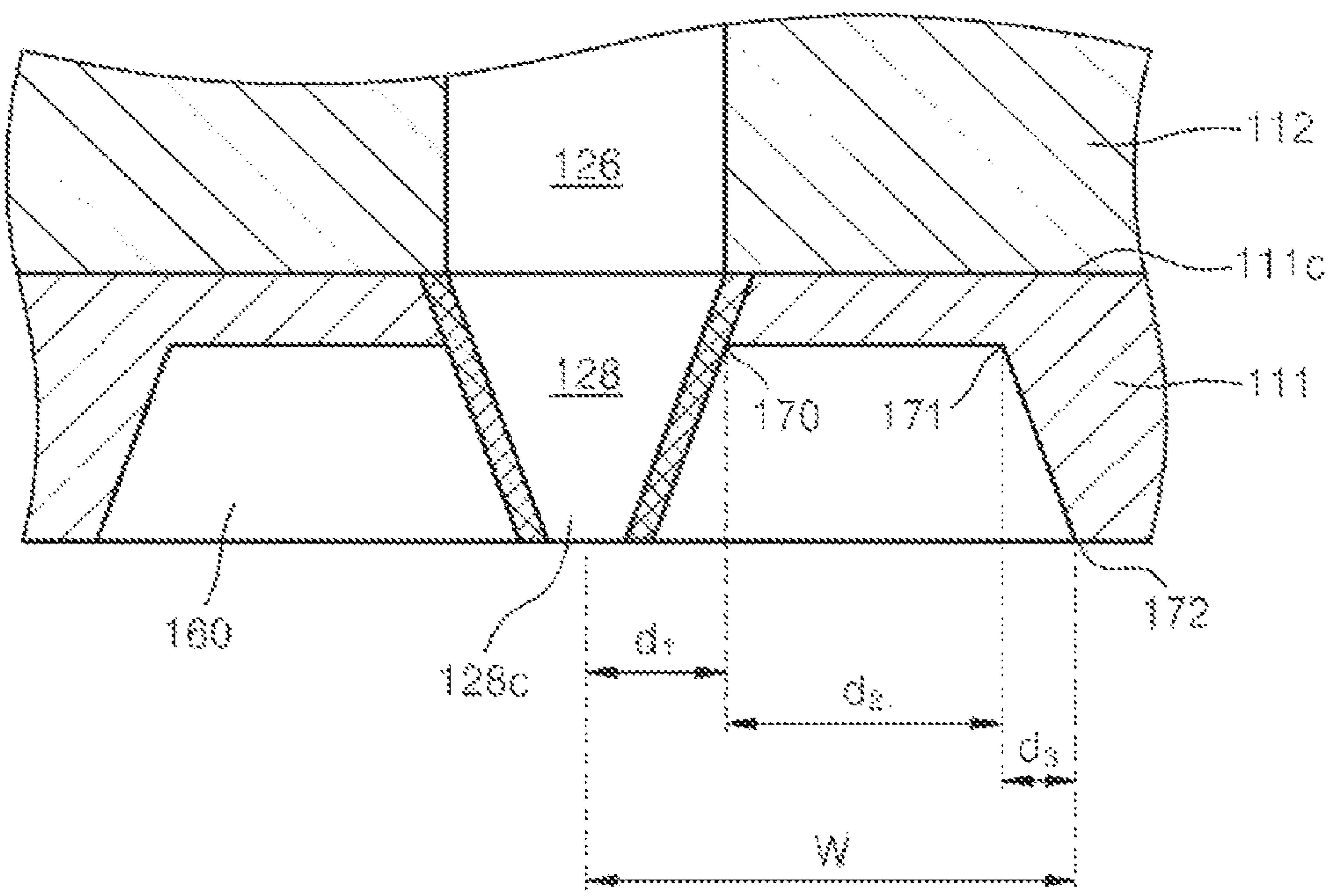

126
112
111c
128
170
171
111
160
128c
172
d1
d2
d3
W

FIG. 7F

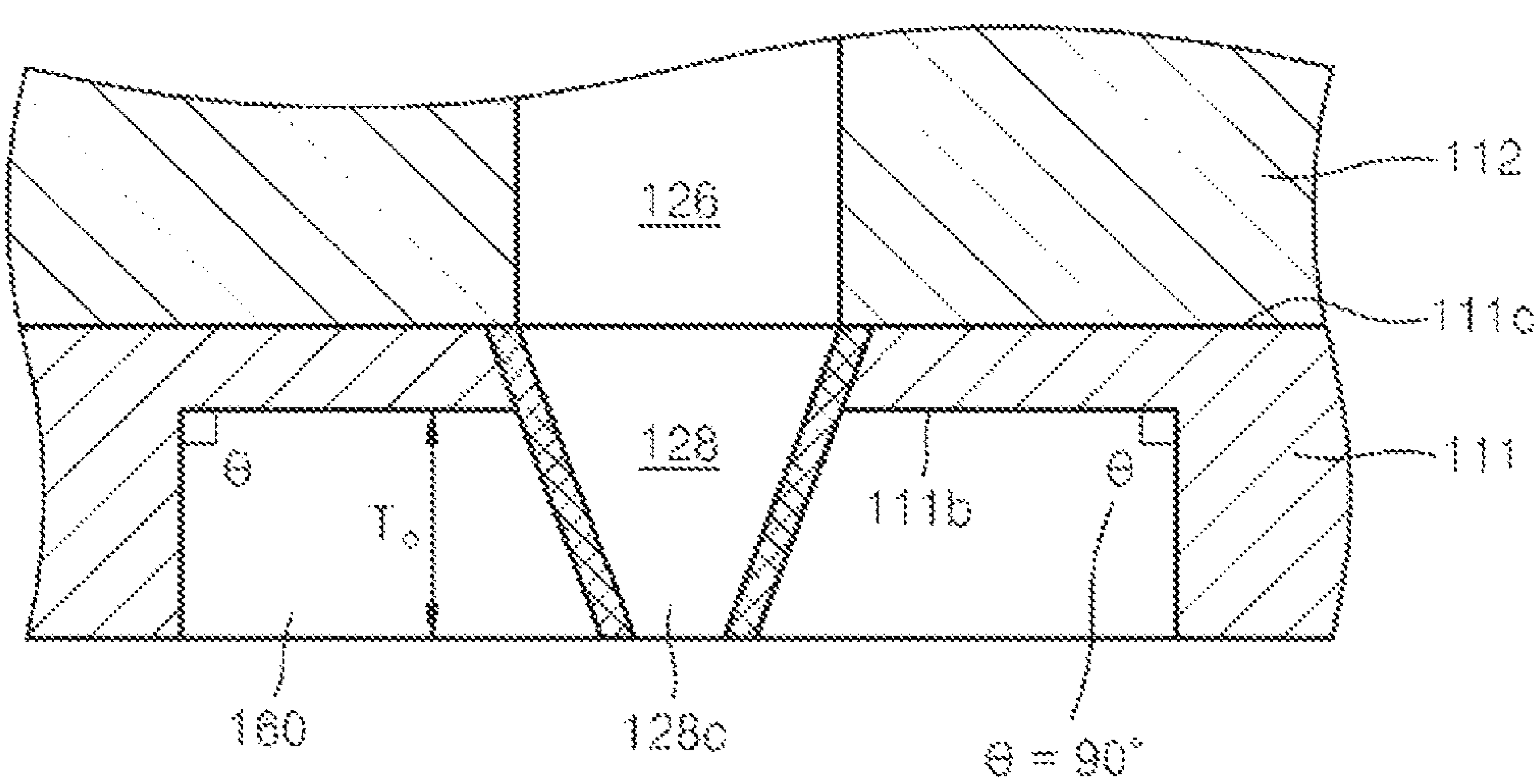

126
112
111c
128
θ
Tc
111b
θ
111
160
128c
θ = 90°

FIG. 7G

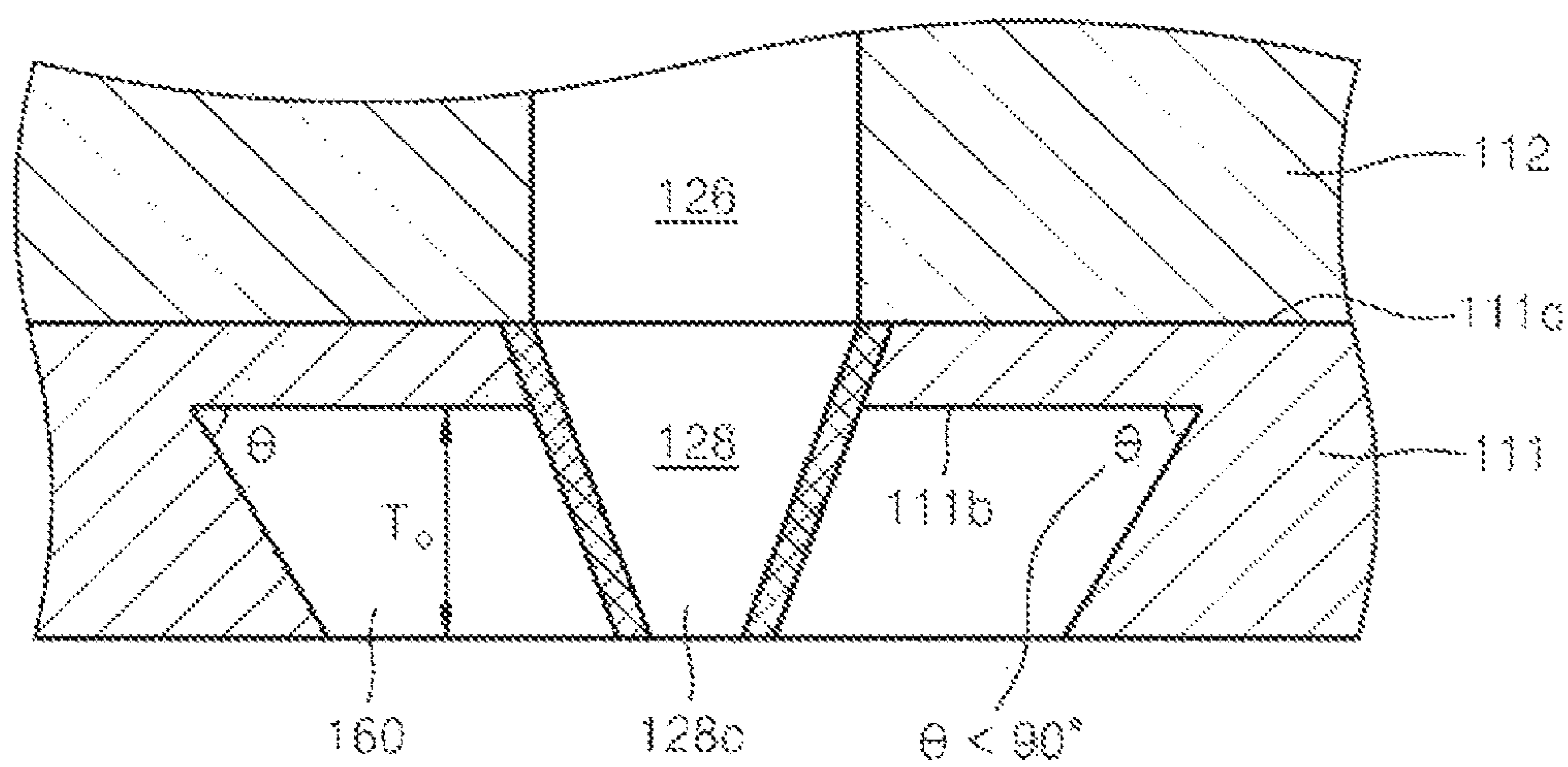


FIG. 8A

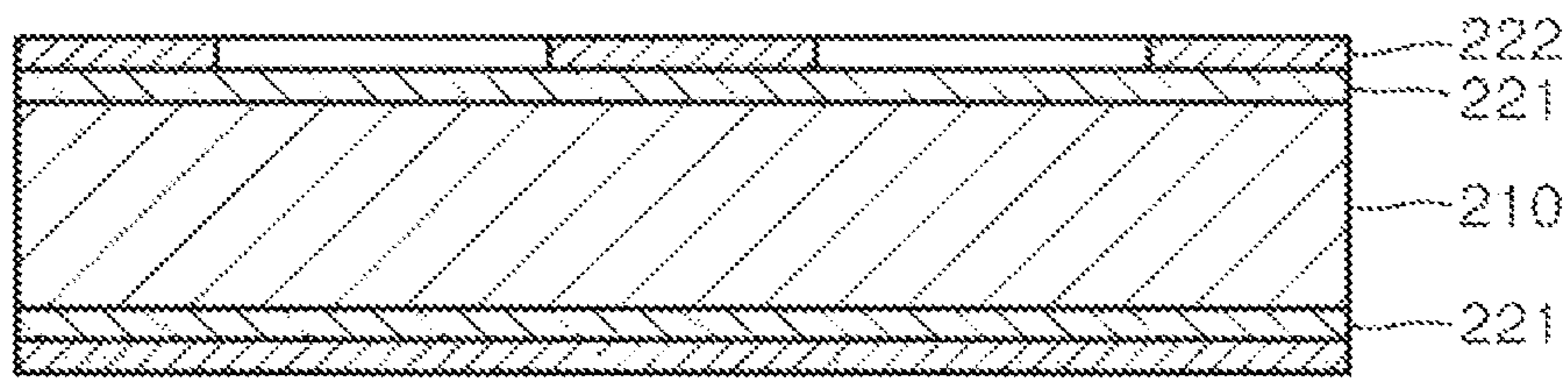


FIG. 8B

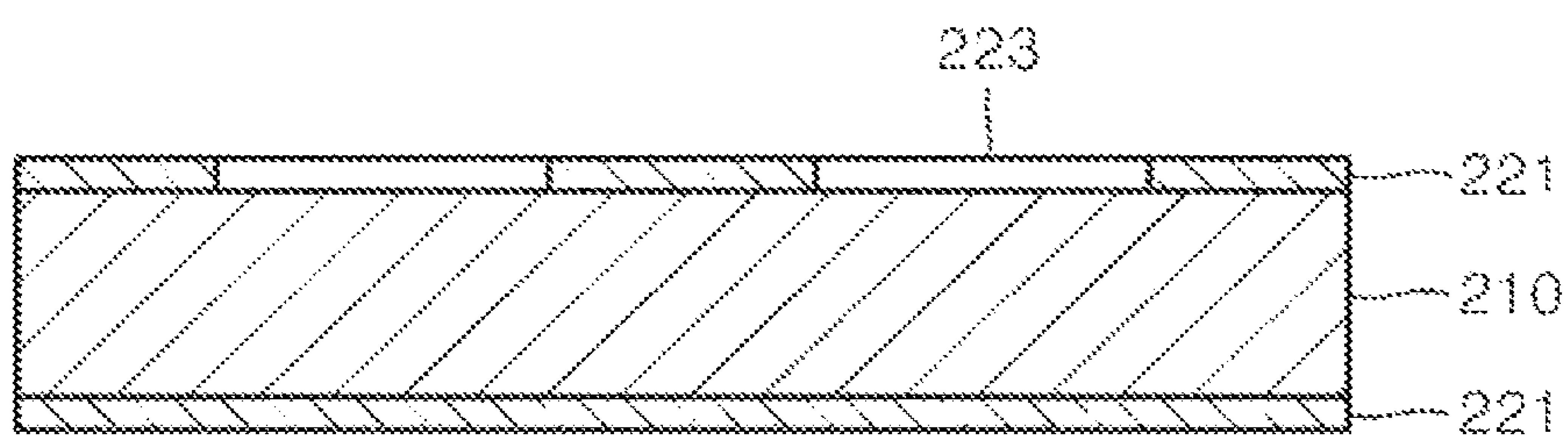


FIG. 8C

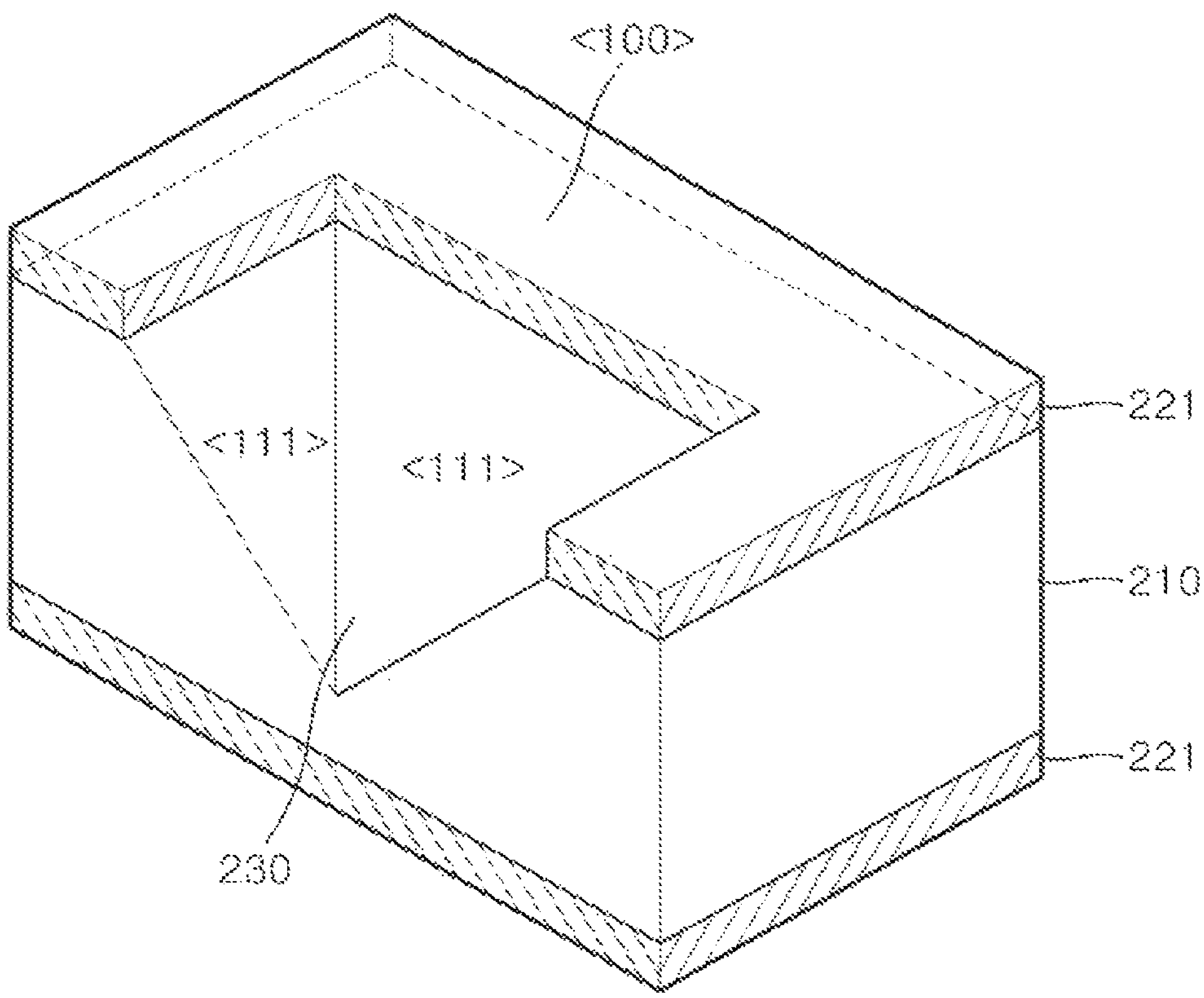


FIG. 8D

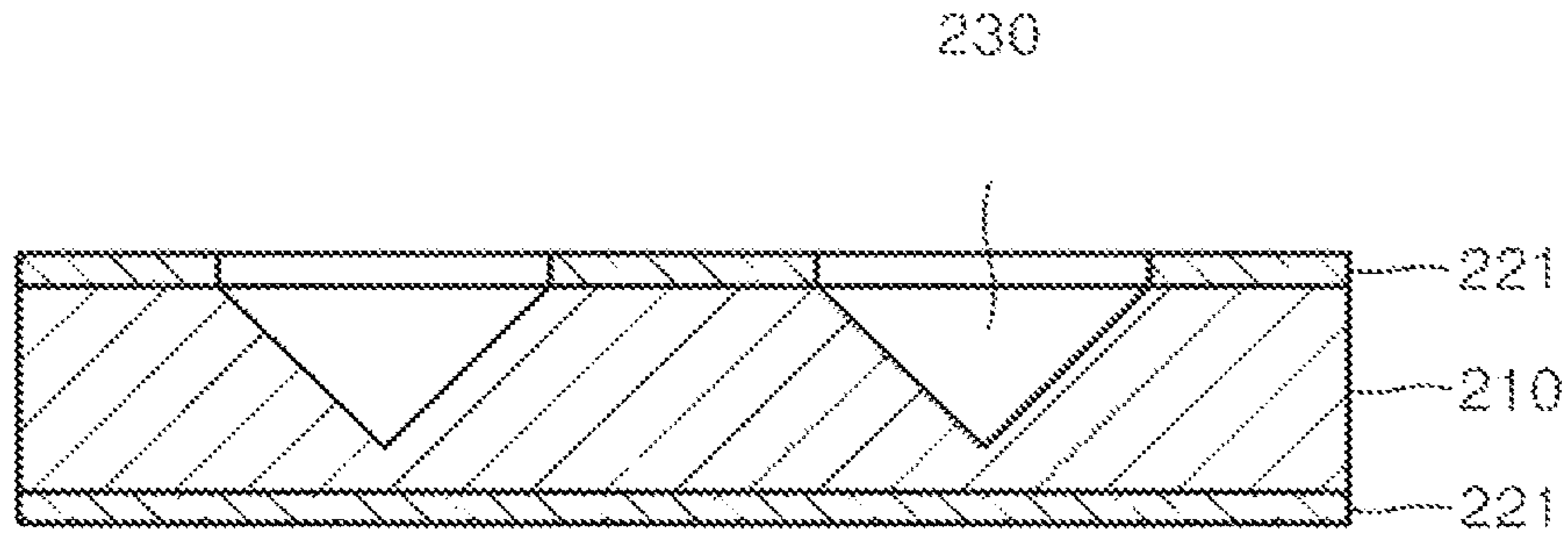


FIG. 8E

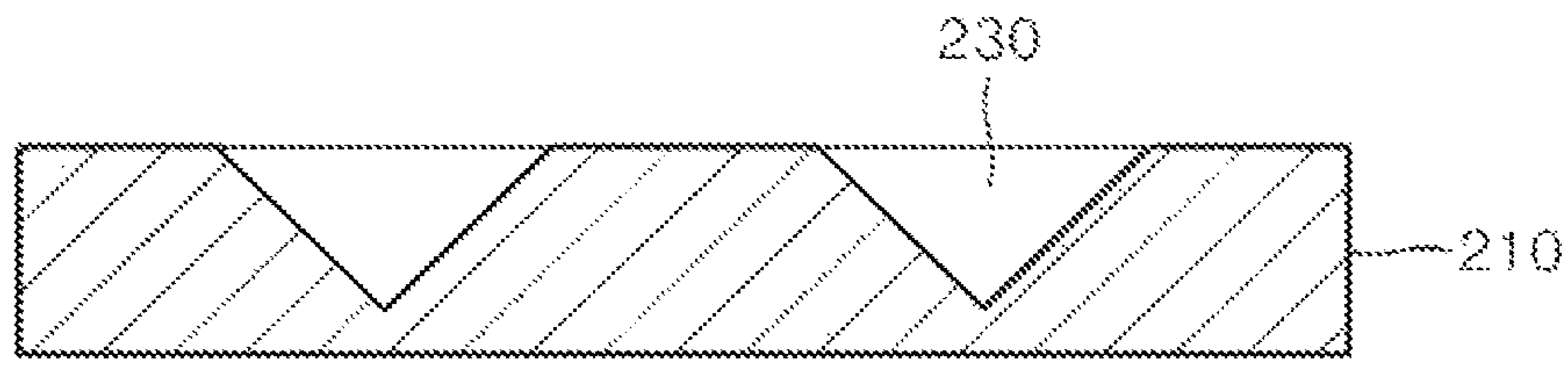


FIG. 8F

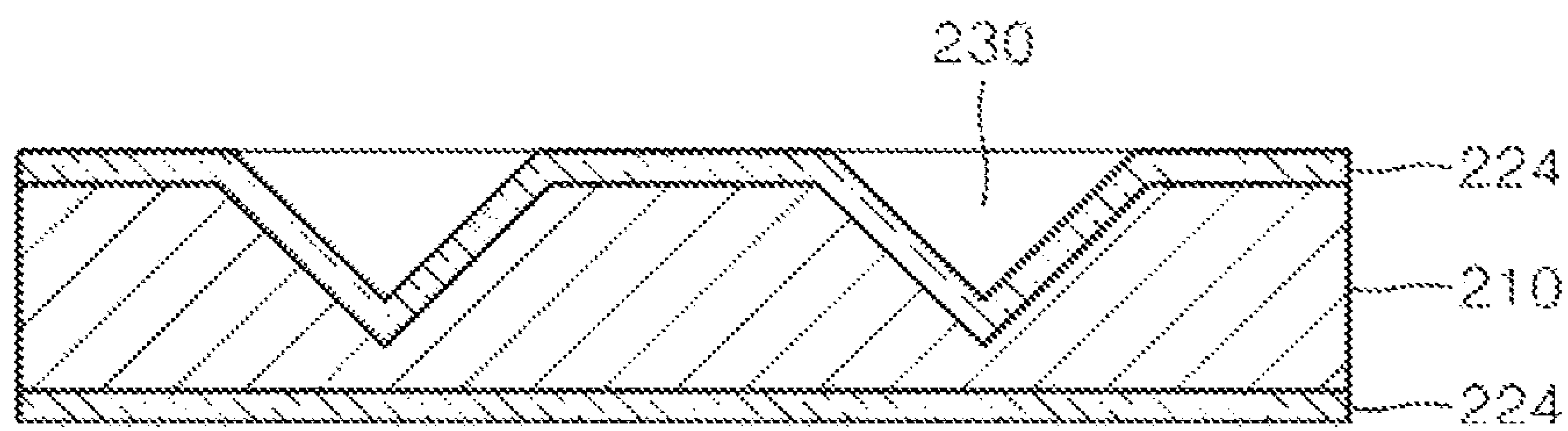


FIG. 8G

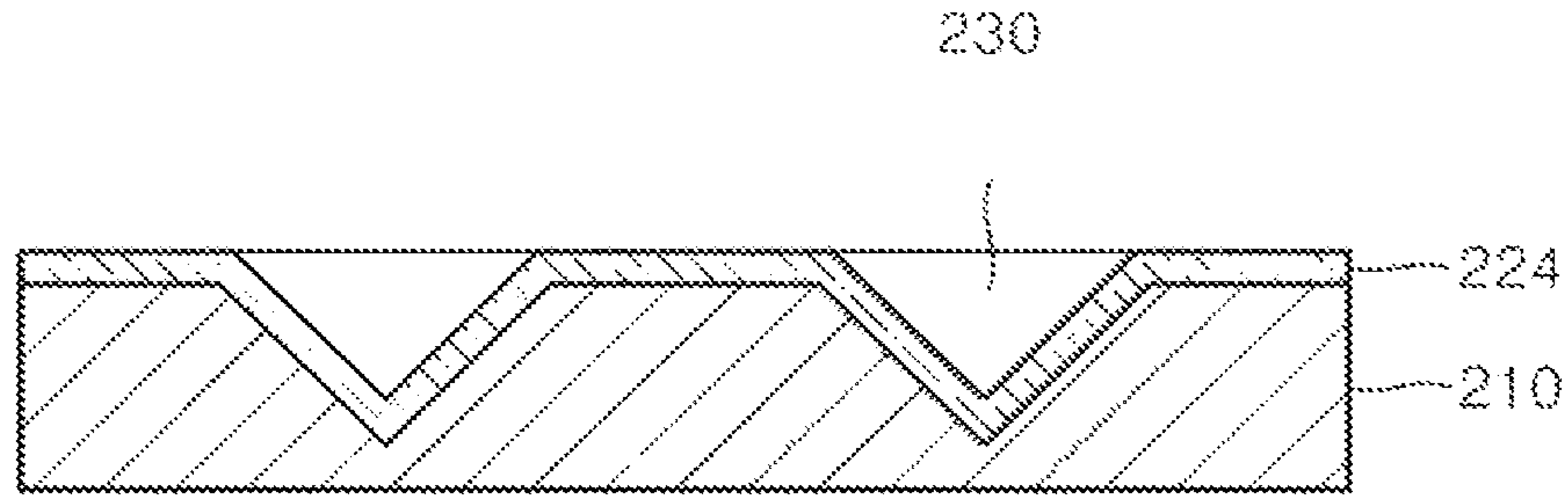


FIG. 8H

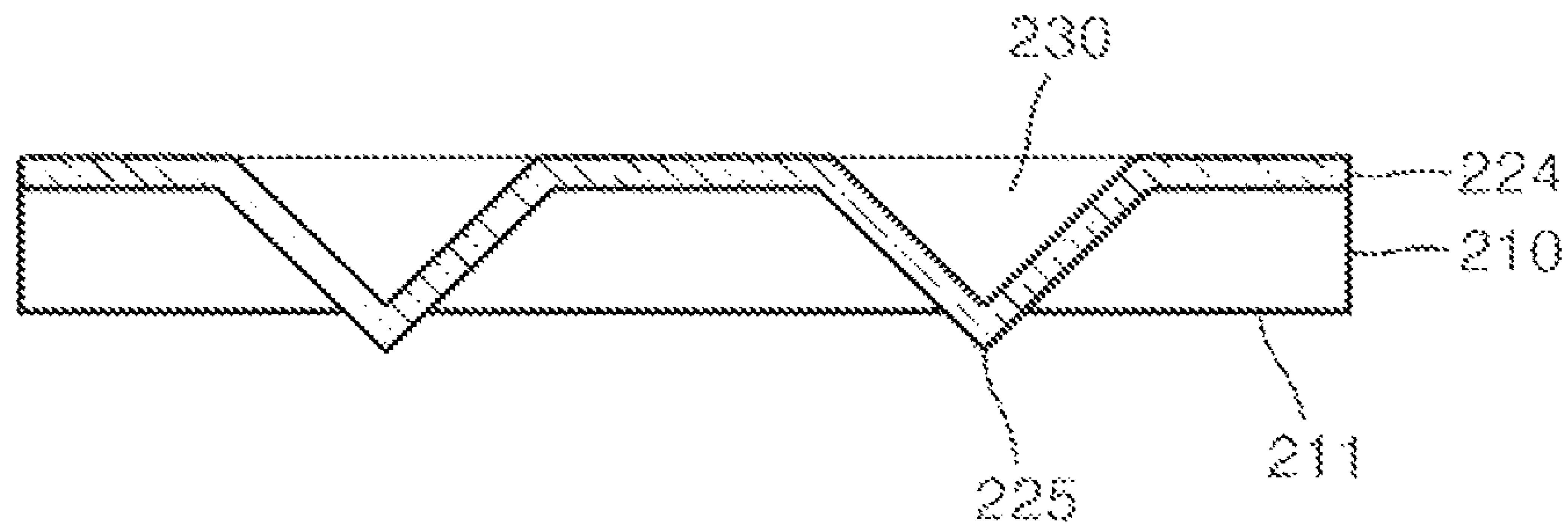


FIG. 8I

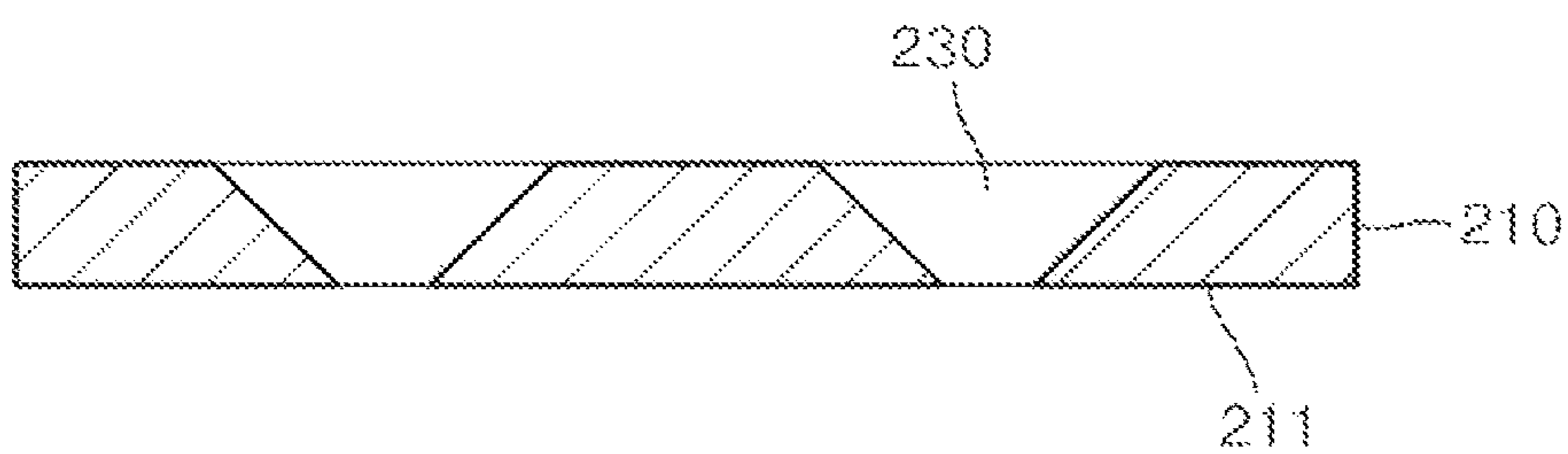


FIG. 8J

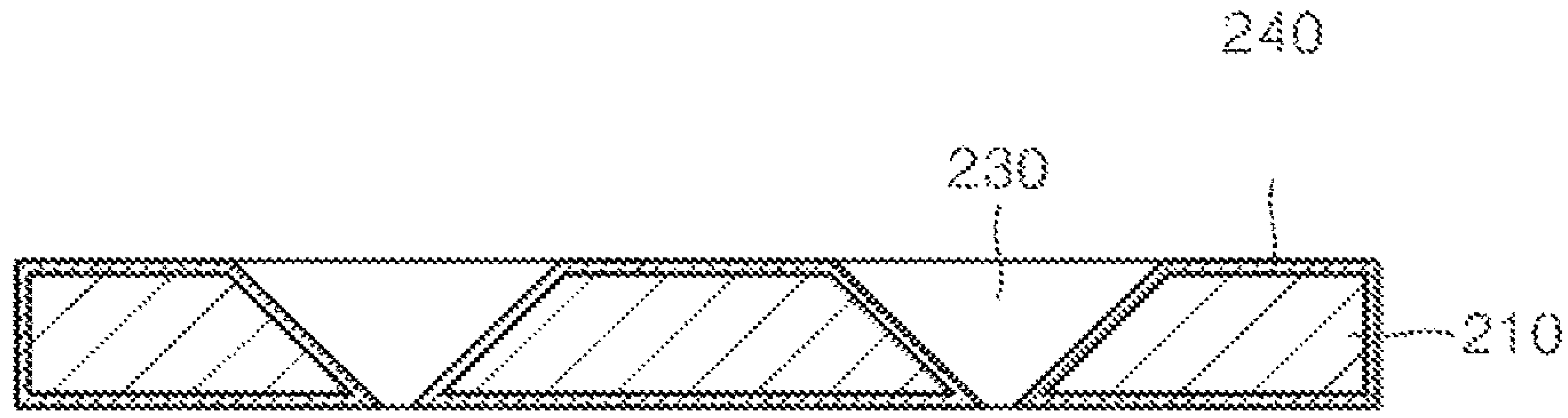


FIG. 8K

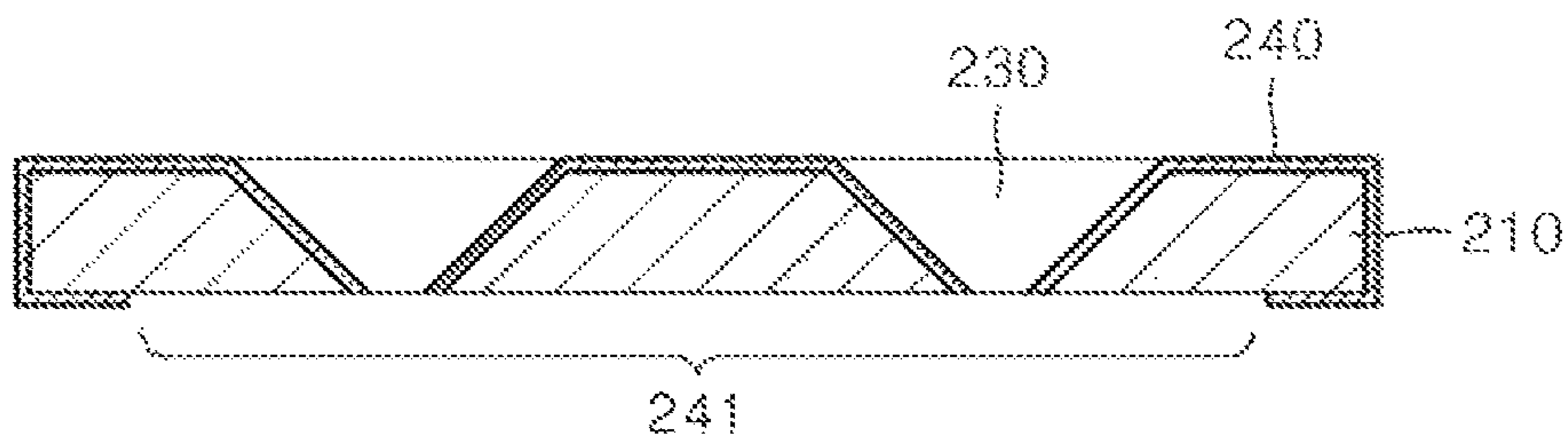


FIG. 8L

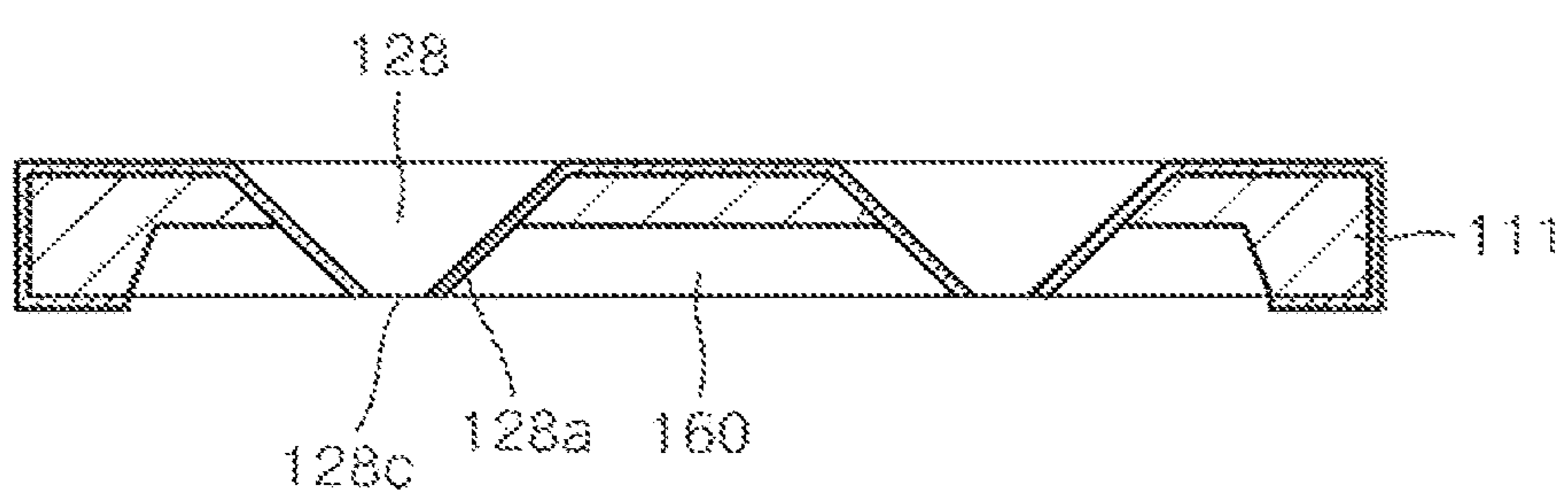


FIG. 9

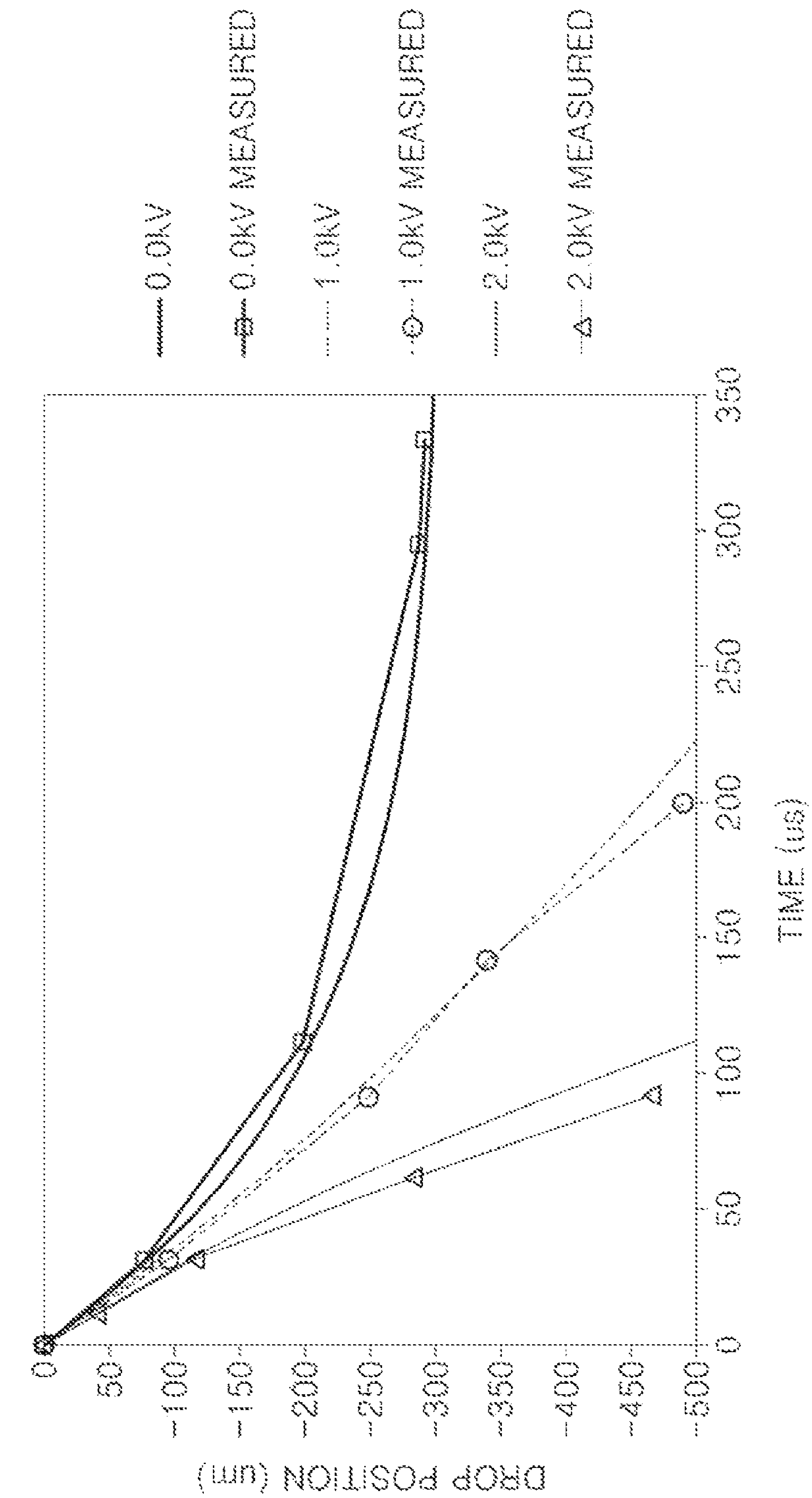
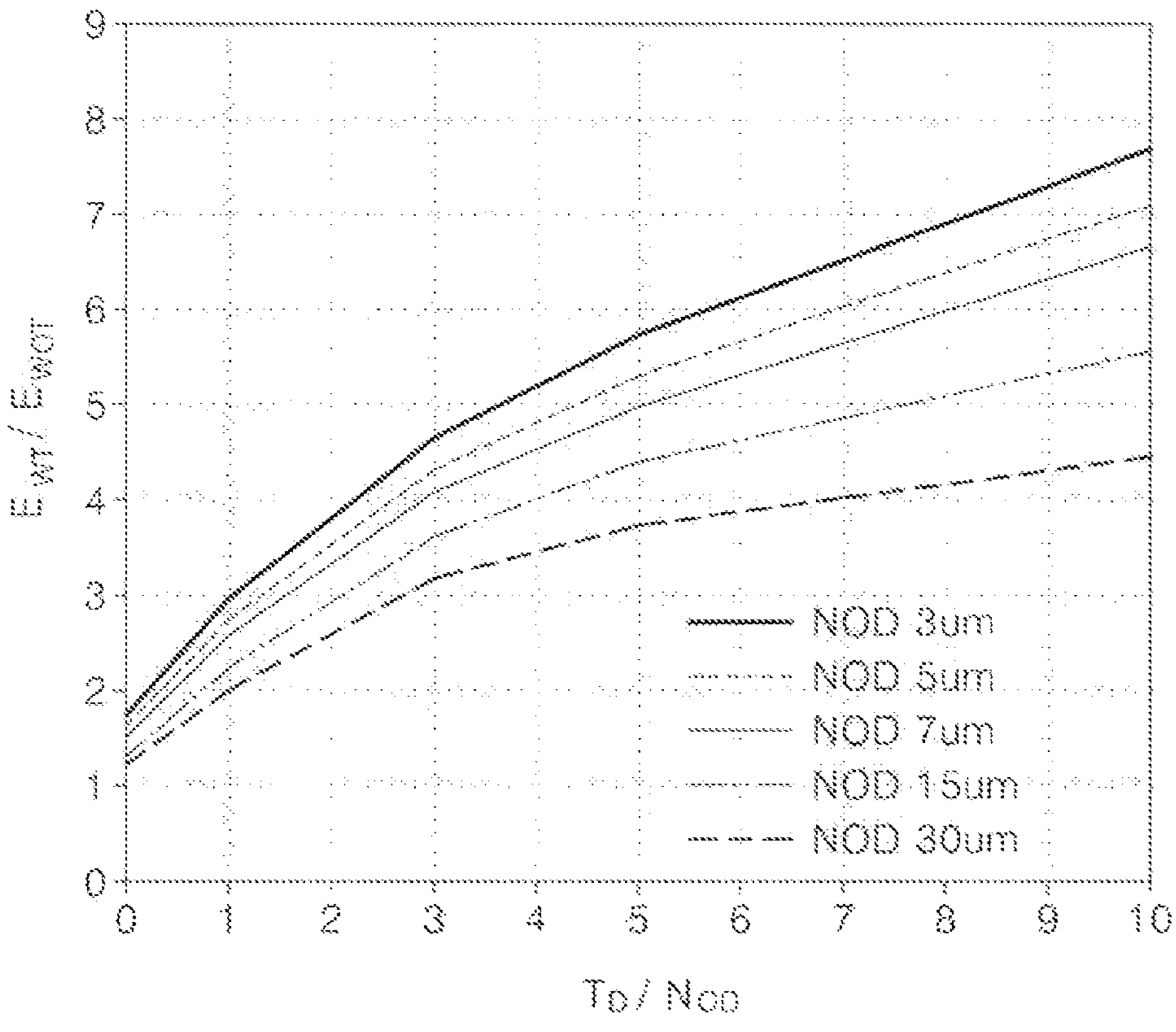

0.0kV
0.0kV MEASURED
1.0kV
1.0kV MEASURED
2.0kV
2.0kV MEASURED
TIME (us)
DROP POSITION (um)
0
50
100
150
200
250
300
350
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500

FIG. 10



9
8
7
6
5
4
3
2
1
0
E_{WT} / E_{WOT}
NOD 3um
NOD 5um
NOD 7um
NOD 15um
NOD 30um
0
1
2
3
4
5
6
7
8
9
10
T_D / N_{OD}

FIG. 11

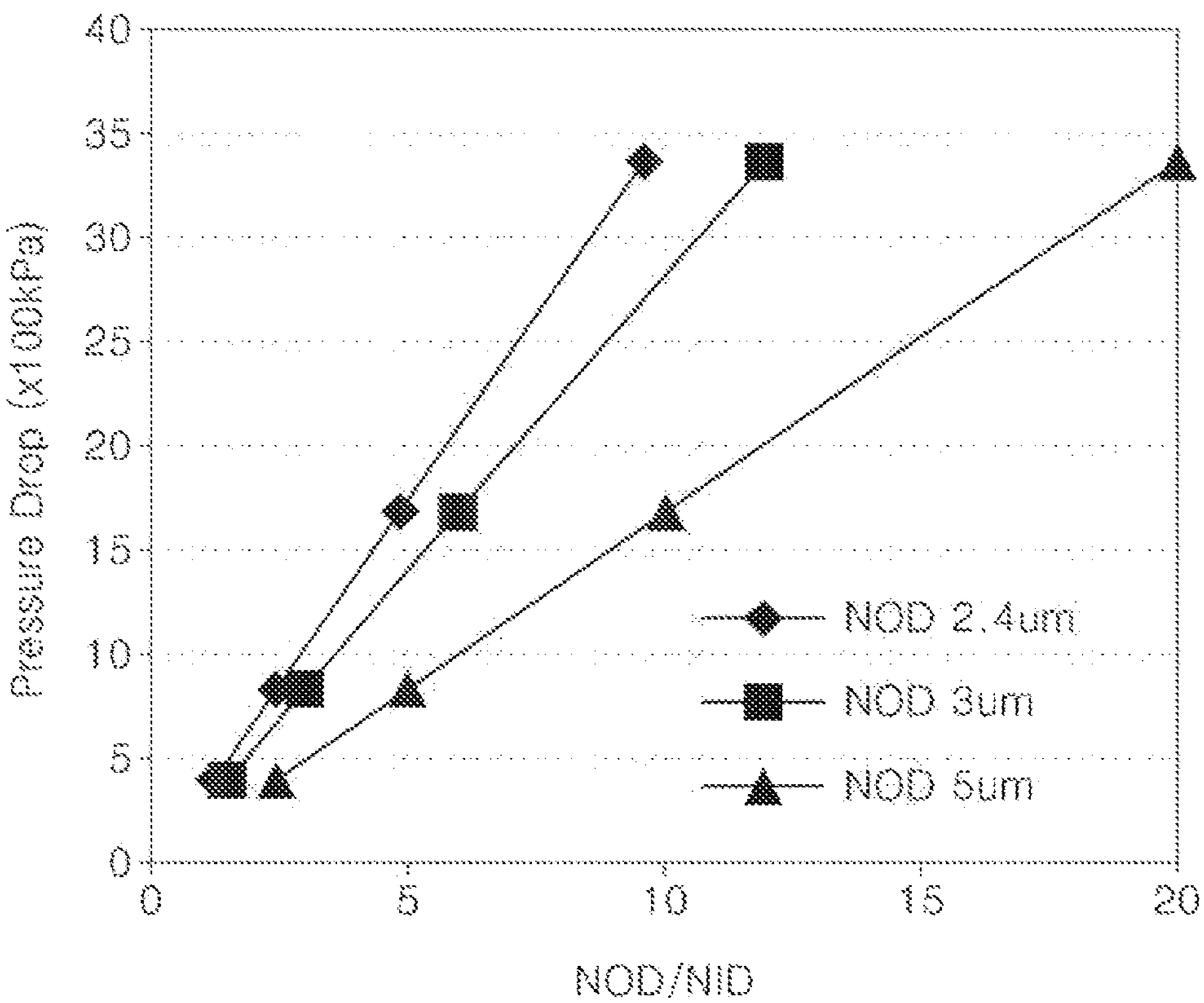

40
35
30
25
20
15
10
5
0
Pressure Drop (x100kPa)
0
5
10
15
20
NOD/NID
NOD 2.4um
NOD 3um
NOD 5um

FIG. 12

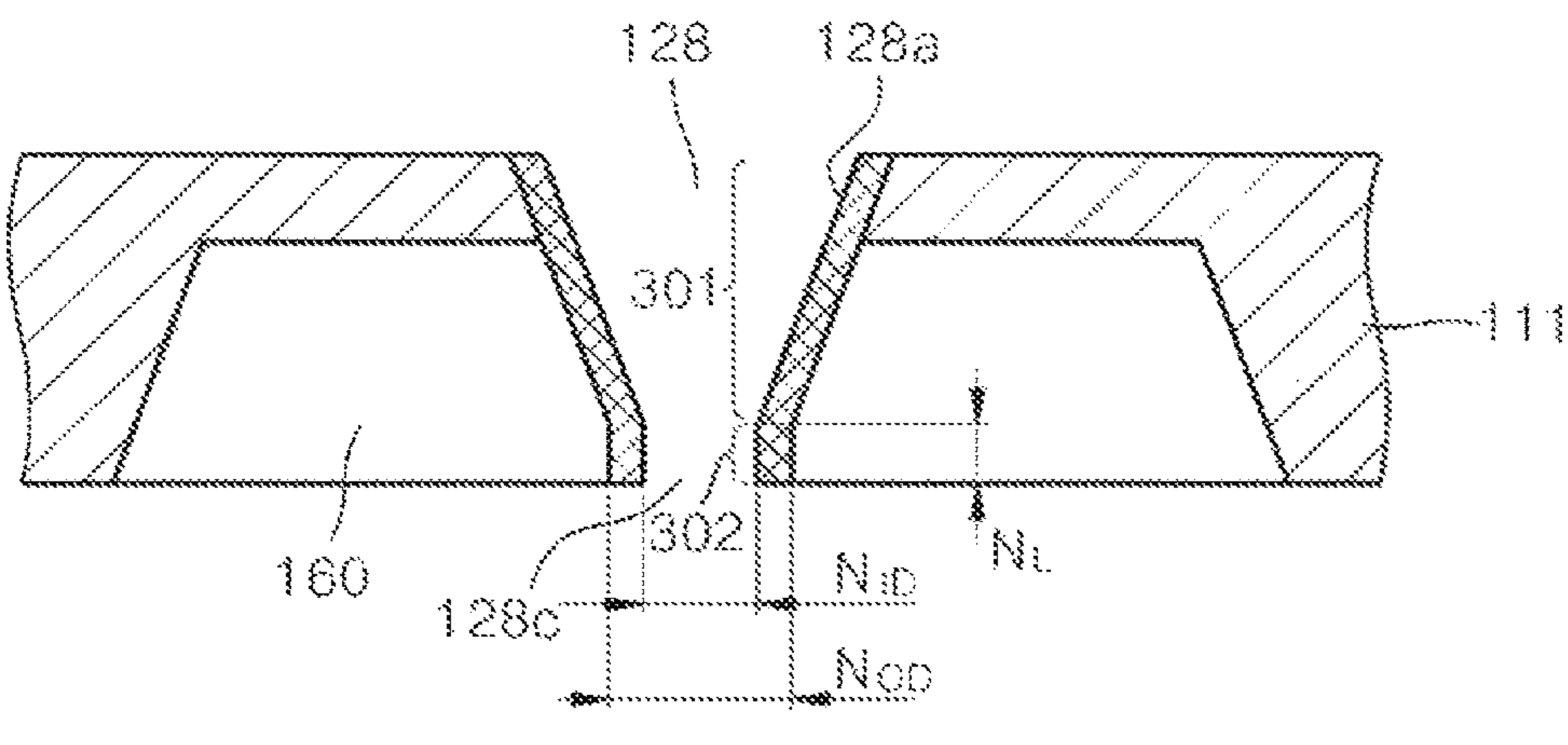


FIG. 13

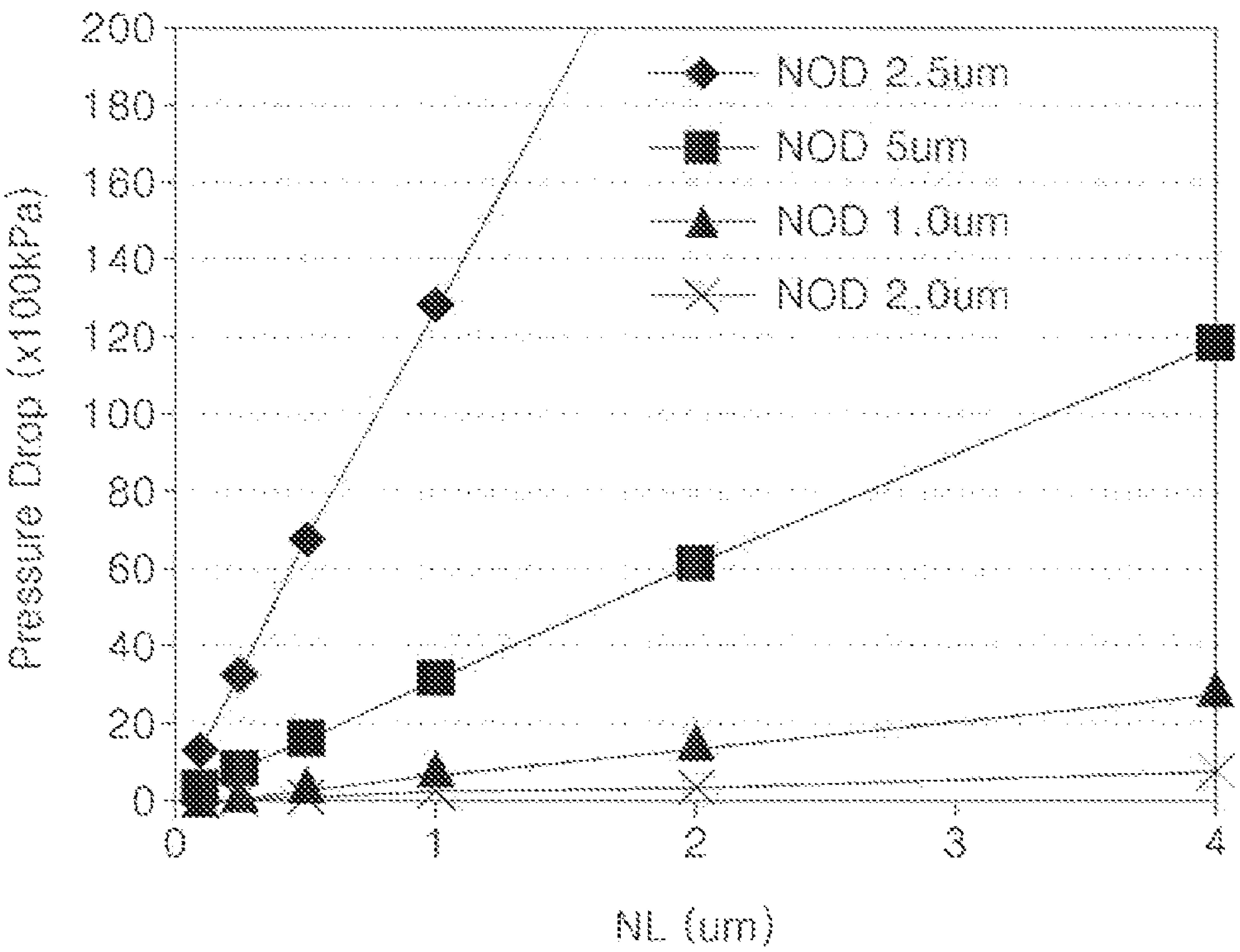

NOD 2.5um
NOD 5um
NOD 1.0um
NOD 2.0um
Pressure Drop (x100kPa)
NL (um)
200
180
160
140
120
100
80
60
40
20
0
0
1
2
3
4

FIG. 14

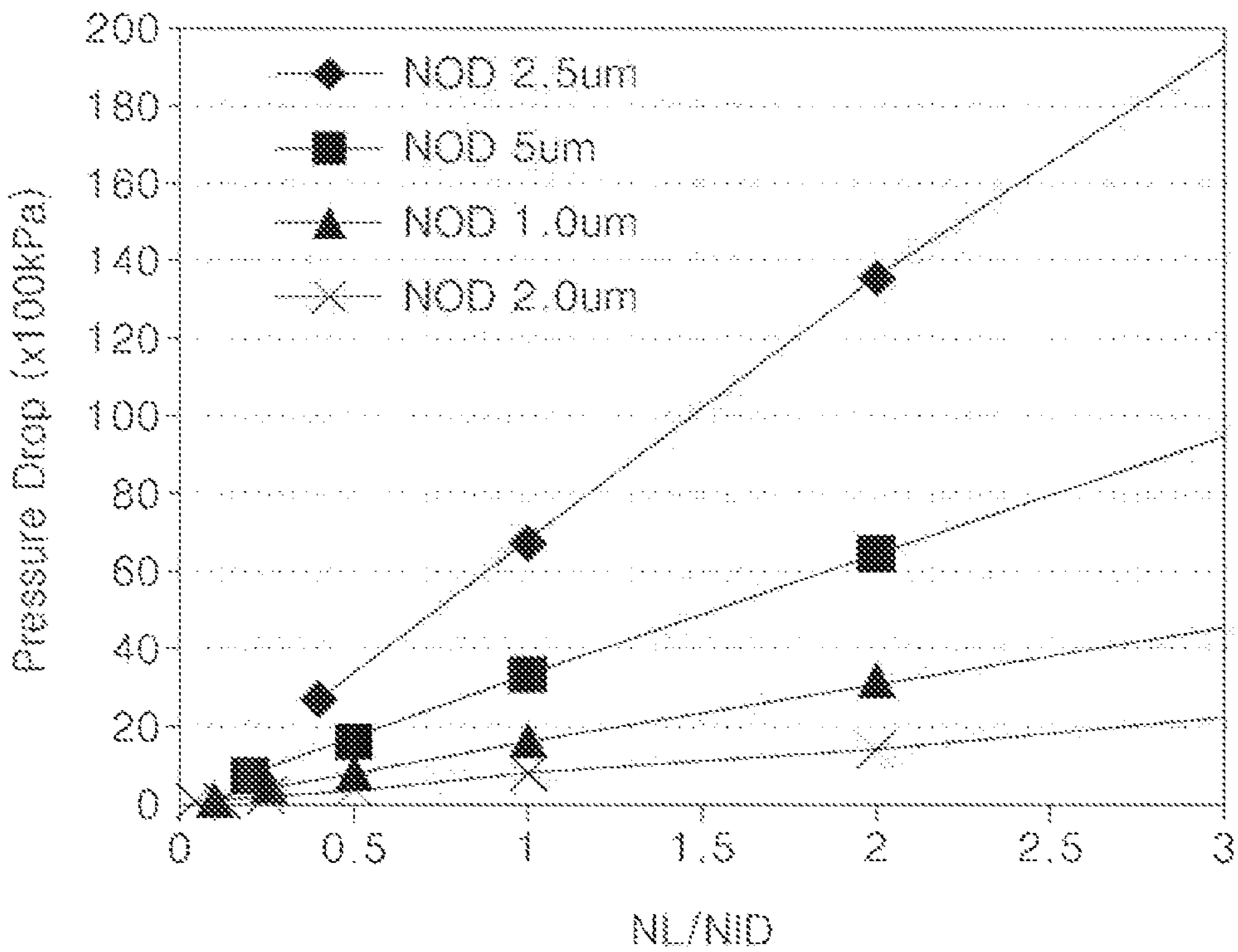

NOD 2.5um
NOD 5um
NOD 1.0um
NOD 2.0um
Pressure Drop (x100kPa)
NL/NID
0
20
40
60
80
100
120
140
160
180
200
0
0.5
1
1.5
2
2.5
3

FIG. 15

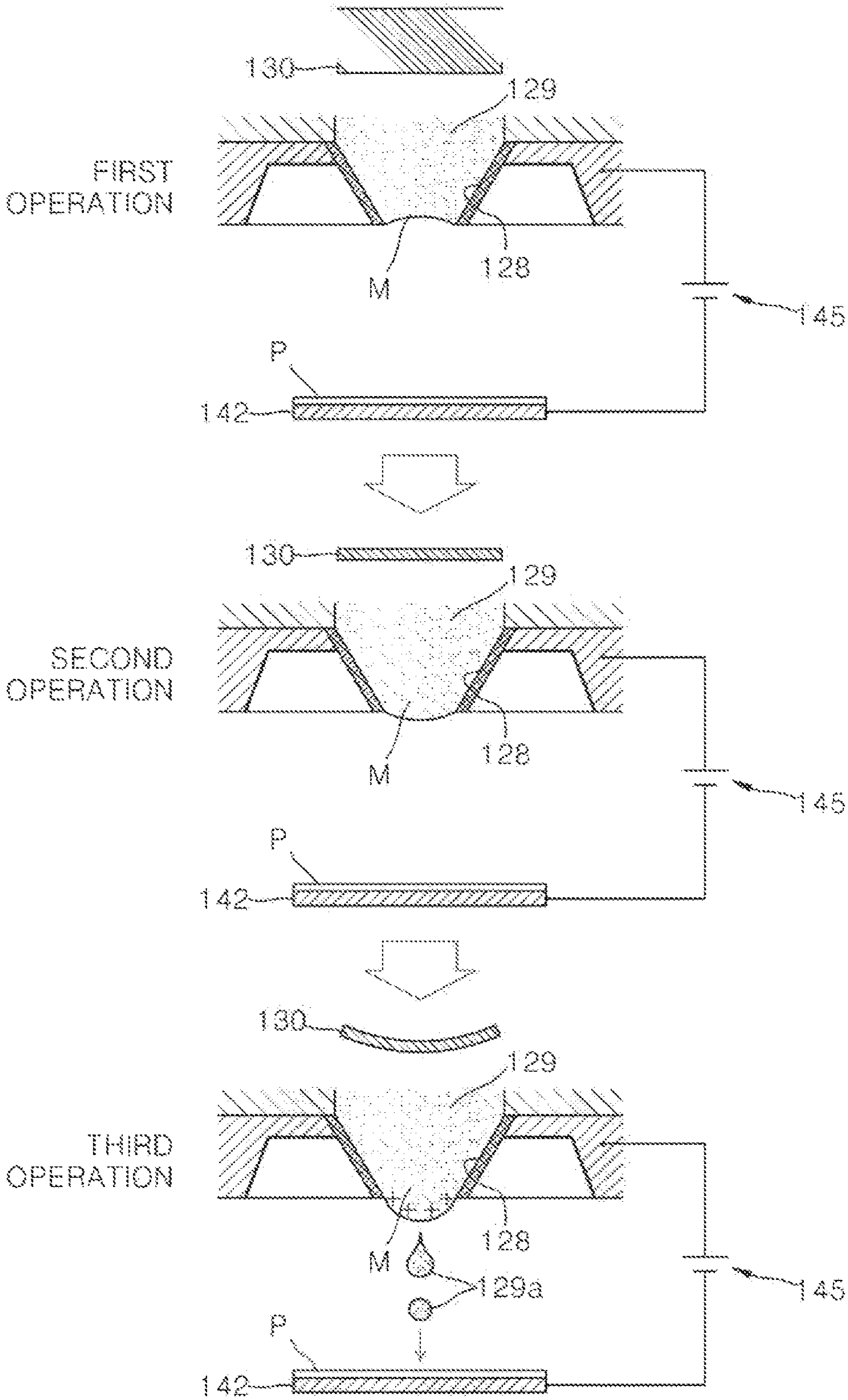

130
129
FIRST OPERATION
128
M
145
P
142
130
129
SECOND OPERATION
128
M
145
P
142
130
129
THIRD OPERATION
128
M
129a
145
P
142

FIG. 16

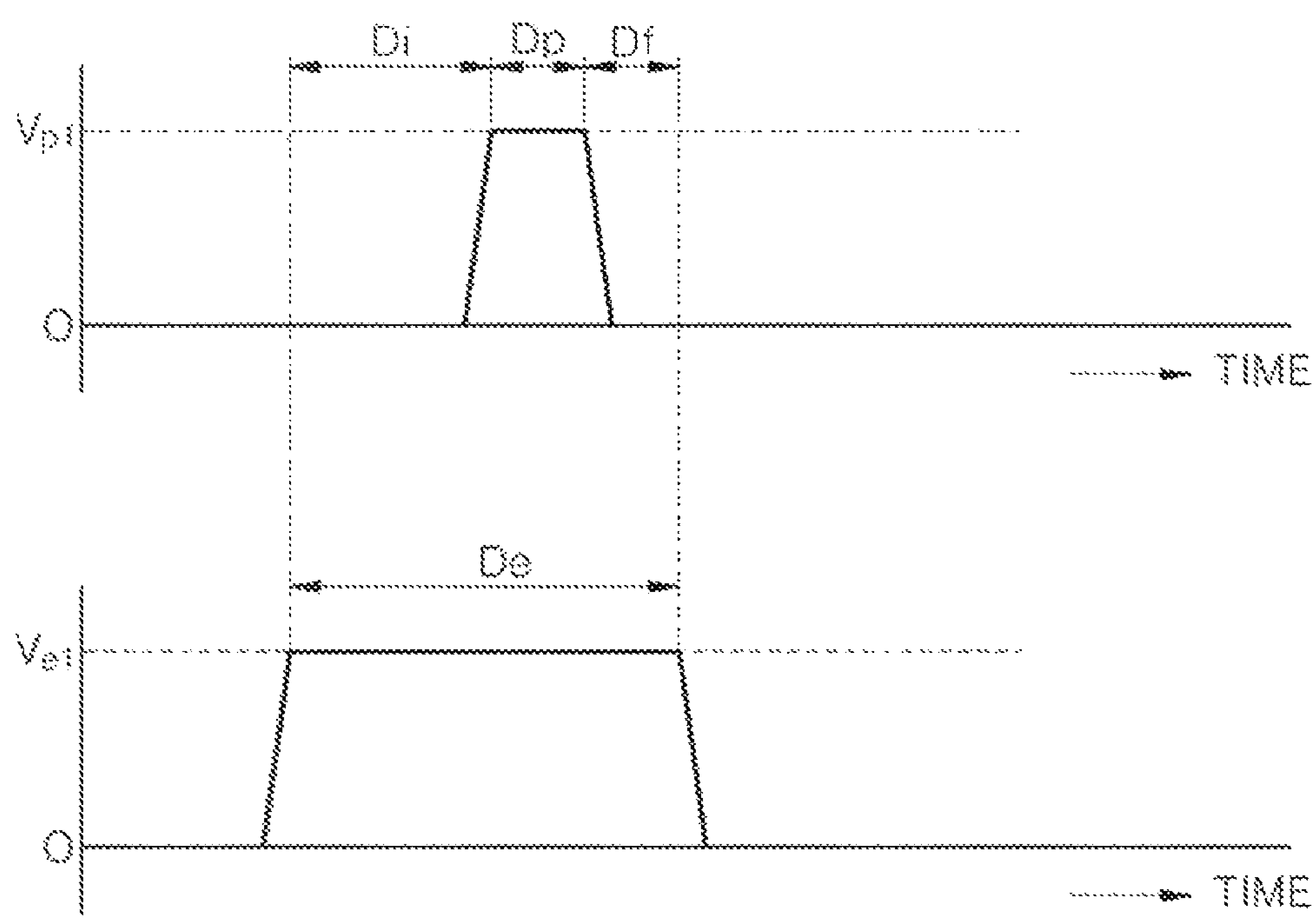


FIG. 17

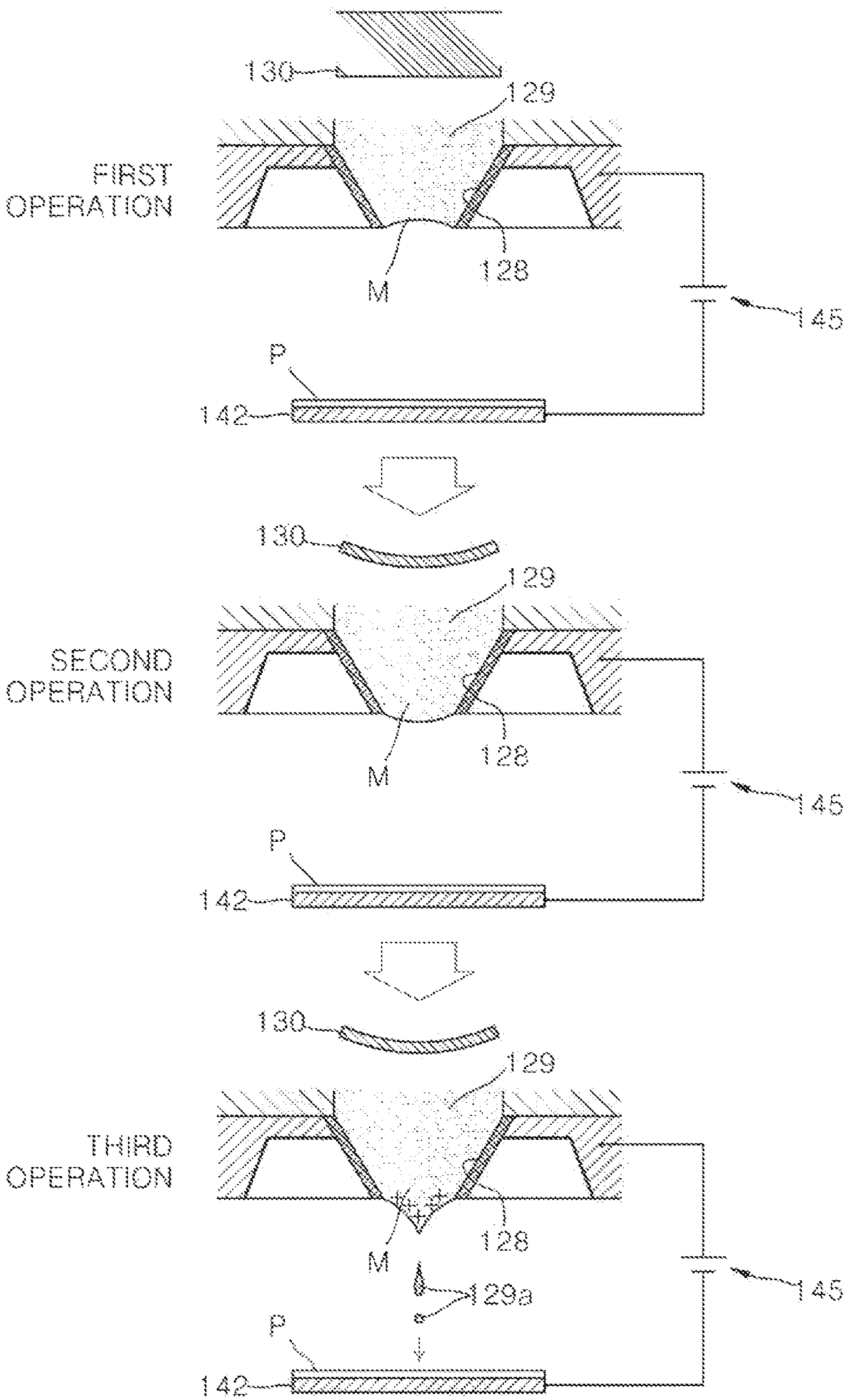

130
129
FIRST
OPERATION
M
128
145
P
142
130
129
SECOND
OPERATION
M
128
145
P
142
130
129
THIRD
OPERATION
M
128
129a
145
P
142

FIG. 18

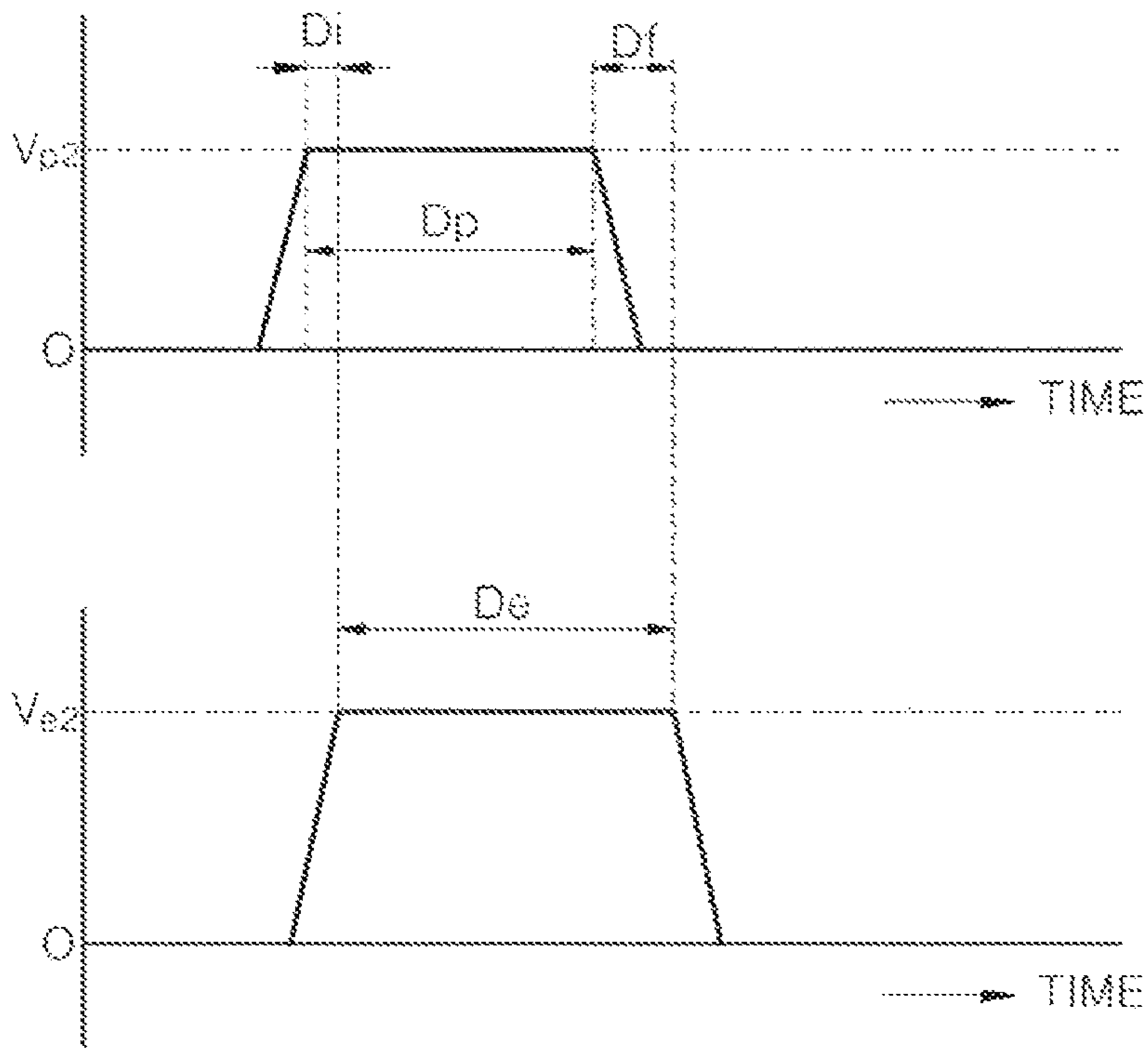


FIG. 19

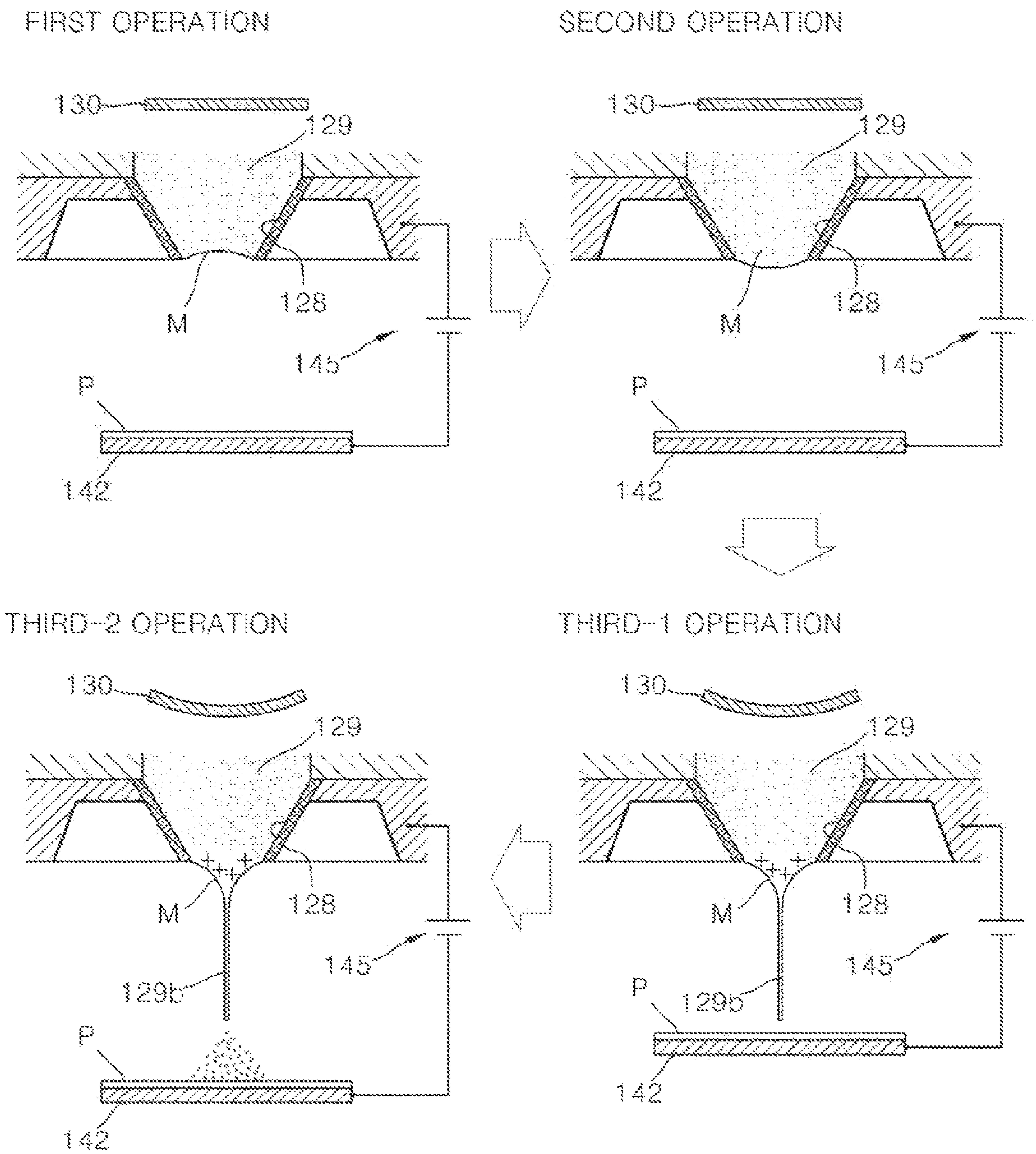

FIRST OPERATION
SECOND OPERATION
THIRD-2 OPERATION
THIRD-1 OPERATION
130
129
128
M
145
P
142
129b

FIG. 20

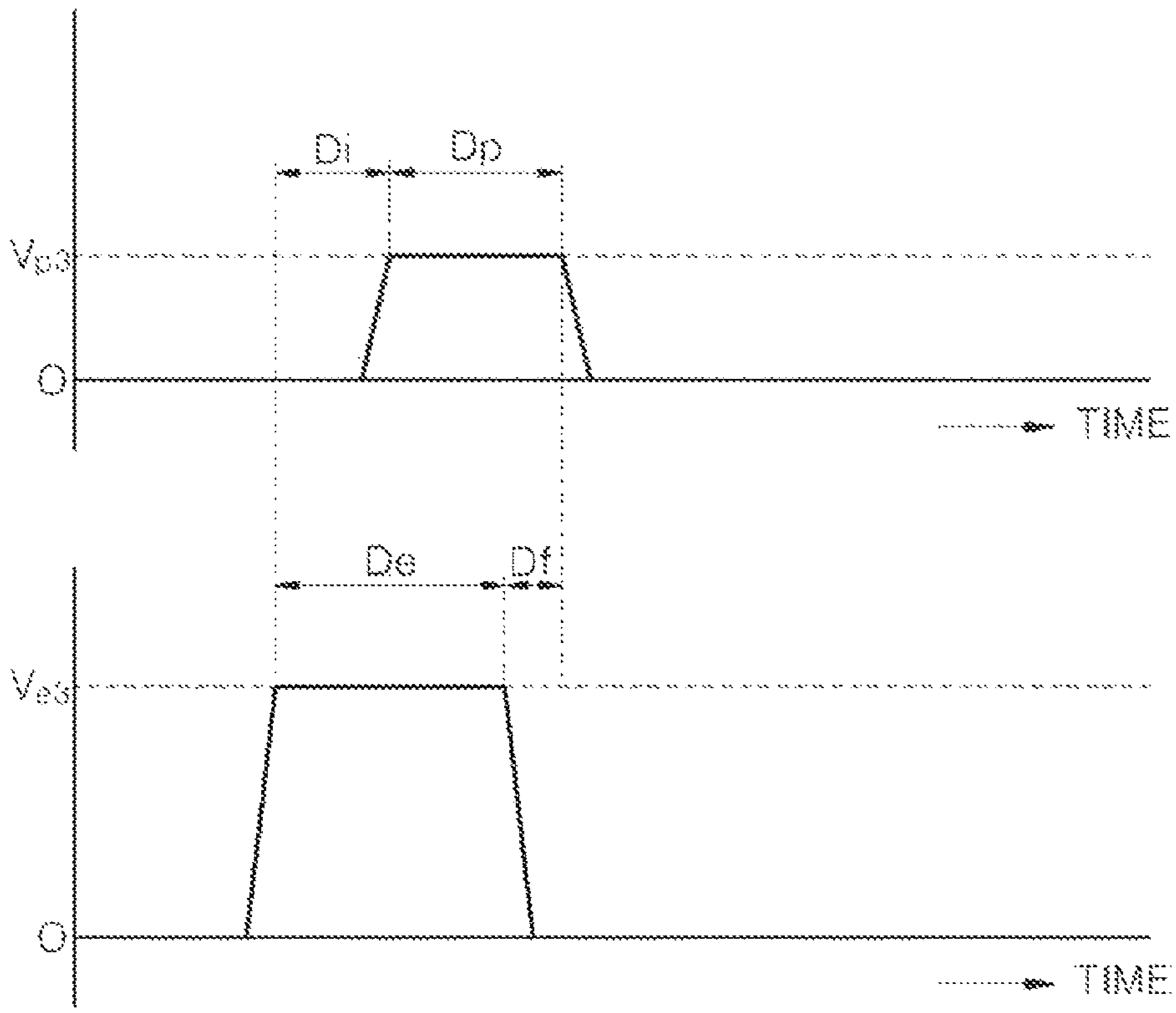


FIG. 21

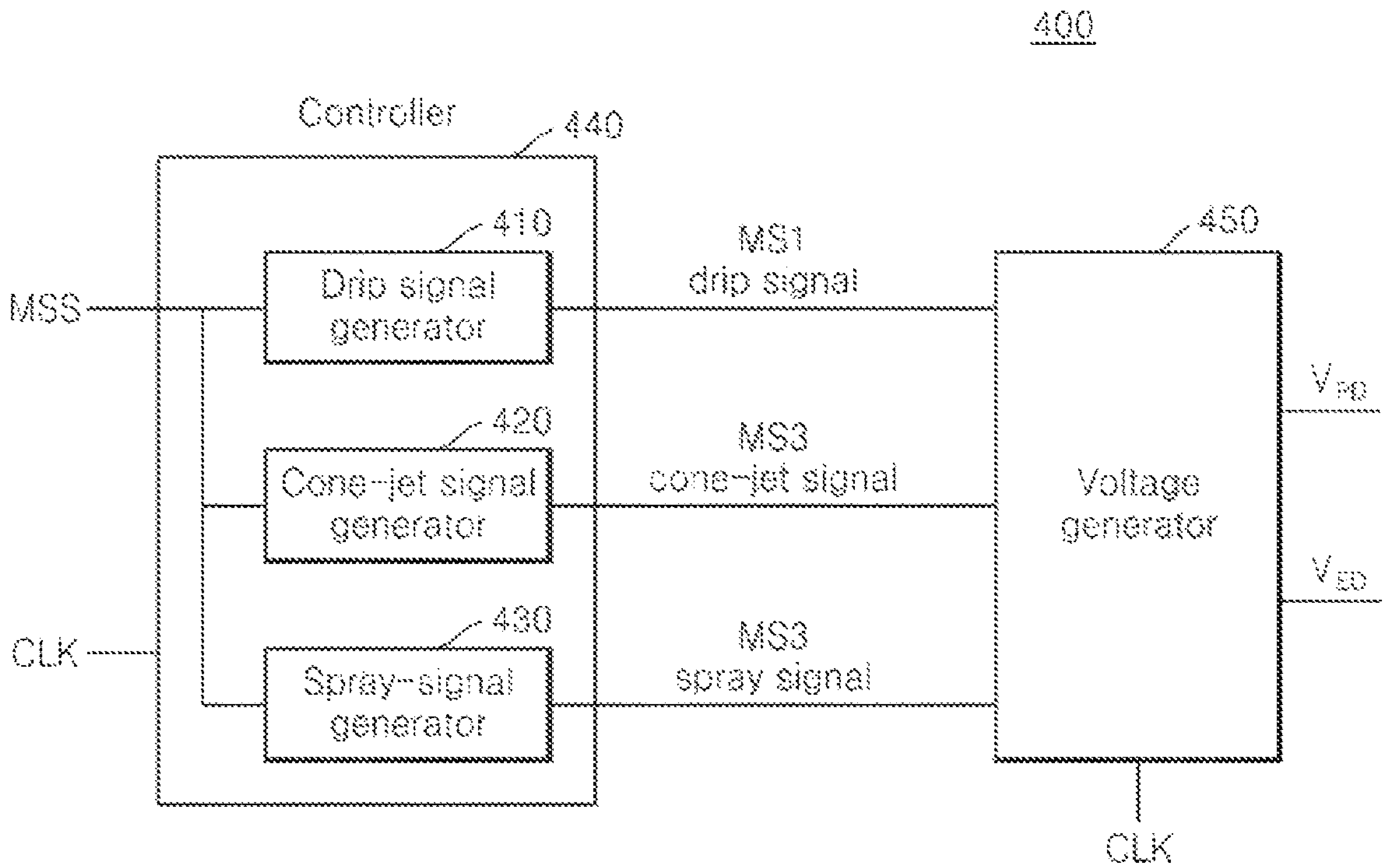
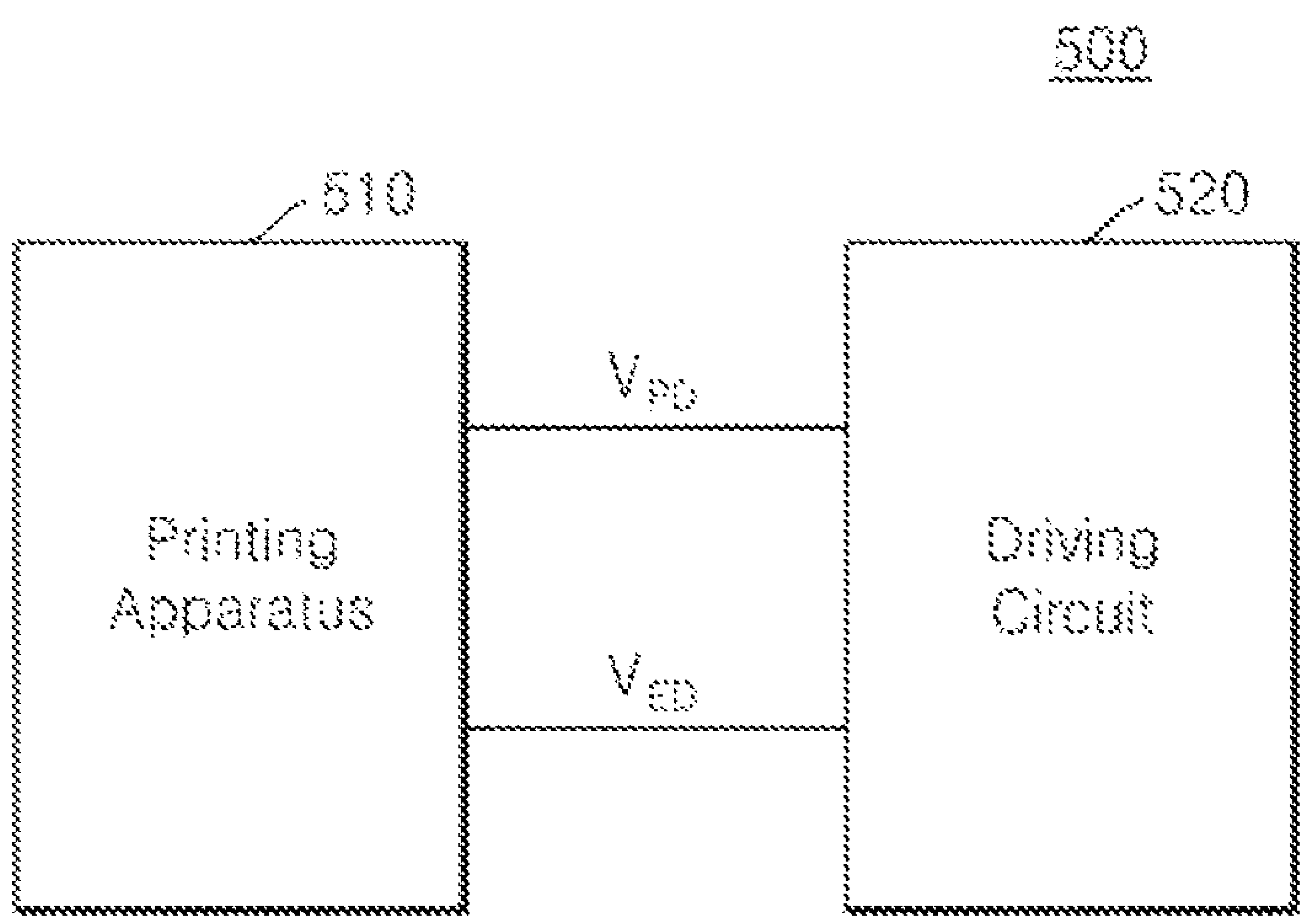

400
Controller
440
410
Drip signal generator
MSS
MS1
drip signal
450
420
Cone-jet signal generator
MS3
cone-jet signal
Voltage generator
V_{PD}
V_{ED}
CLK
430
Spray-signal generator
MS3
spray signal
CLK

FIG. 22


500
510
520
Printing Apparatus
V_{PD}
V_{ED}
Driving Circuit

PRINTING SYSTEM, PRINTING APPARATUSES, AND METHODS OF FORMING NOZZLES OF PRINTING APPARATUSES

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a Divisional application of U.S. application Ser. No. 13/604,269, filed on Sep. 5, 2012, which claims the benefit of Korean Patent Application No. 10-2011-0091319, filed on Sep. 8, 2011, in the Korean Intellectual Property Office, the disclosures of which are incorporated herein in their entirety by reference.

BACKGROUND

1. Field

At least one example embodiment relates to a printing apparatus, and more particularly, to a composite-type inkjet printing apparatus employing piezoelectric and/or electrostatic methods.

2. Description of the Related Art

Inkjet printing apparatuses print a predetermined image by ejecting minute droplets of ink on desired areas of a printing medium.

An inkjet printing apparatus may be classified as a piezoelectric-type inkjet printing apparatus or an electrostatic-type inkjet printing apparatus according to an ink ejecting method. A piezoelectric-type inkjet printing apparatus ejects ink via piezoelectric deformation, and an electrostatic-type inkjet printing apparatus ejects ink via an electrostatic force. An electrostatic-type inkjet printing apparatus may use a method of ejecting ink droplets by electrostatic induction or a method of ejecting ink droplets after accumulating charged pigments via an electrostatic force.

SUMMARY

At least one example embodiment provides a printing apparatus capable of ejecting minute droplets (e.g., droplets having volumes of several femtoliters) at a high position accuracy by using a drop on demand (DOD) method.

Additional aspects will be set forth in part in the description which follows and, in part, will be apparent from the description, or may be learned by practice of example embodiments.

According to at least one example embodiment, a printing apparatus comprises: a flow channel plate including, a pressure chamber, a nozzle including an outlet through which ink contained in the pressure chamber is ejected, and a trench disposed around the nozzle, and the outlet extending into the trench; a piezoelectric actuator configured to provide a change in pressure to eject the ink contained in the pressure chamber; and an electrostatic actuator configured to provide an electrostatic driving force to the ink contained in the nozzle.

According to at least one example embodiment, the nozzle includes a tapered portion of which a size of a cross-sectional area decreases toward the outlet.

According to at least one example embodiment, a nozzle wall that forms a boundary between the nozzle and the flow channel plate extends into the trench.

According to at least one example embodiment, the nozzle has a polypyramid shape.

According to at least one example embodiment, the nozzle wall is formed of at least one of SiO_2, SiN, Si, Ti, Pt, and Ni.

According to at least one example embodiment, the flow channel plate comprises: a channel forming substrate in which an ink channel is formed, and a nozzle substrate in which the nozzle and the trench are formed, the nozzle substrate being joined to the channel forming substrate, and the nozzle substrate being a single crystal silicon substrate.

According to at least one example embodiment, the nozzle wall is formed of SiO_2.

According to at least one example embodiment, the SiO_2 is formed by oxidizing the nozzle substrate.

According to at least one example embodiment, an outer diameter of the outlet of the nozzle is N_{OD} and a depth of the trench is T_D, and a ratio of T_D to N_{OD} is greater than 1.

According to at least one example embodiment, the outer diameter and an inner diameter of the outlet of the nozzle are N_{OD} and N_{ID}, respectively, and a ratio of N_{OD} to N_{ID} is less than 5.

According to at least one example embodiment, the nozzle includes: an extension portion linearly extending from the tapered portion, and an inner diameter of the outlet of the nozzle is N_{ID} and a length of the extension portion is N_L, and a ratio of N_L to N_{ID} is greater than or equal to 0 and less than 1.

According to at least one example embodiment, a printing apparatus comprises: a channel forming substrate including a pressure chamber; a nozzle substrate including an upper surface, a lower surface, and a trench surface formed between the upper surface and the lower surface so as to differ in level from the upper and lower surfaces; and a nozzle including an outlet through which ink contained in the pressure chamber is ejected, that the nozzle extending toward the lower surface from the upper surface of the nozzle substrate so as to have a tapered shape in which a size of a cross-sectional area of the nozzle is gradually reduced, and the nozzle penetrating the trench surface.

According to at least one example embodiment, the nozzle substrate is a single crystal silicon substrate, and the nozzle is formed of SiO_2.

According to at least one example embodiment, an outer diameter of the outlet of the nozzle is N_{OD} and a depth of the trench surface from the lower surface is T_D, and a ratio of T_D to N_{OD} is greater than 1.

According to at least one example embodiment, the outer diameter and an inner diameter of the outlet of the nozzle are N_{OD} and N_{ID}, respectively, and a ratio of N_{OD} to N_{ID} is less than 5.

According to at least one example embodiment, the nozzle comprises: an extension portion linearly extending downward from a portion having a tapered shape, and he inner diameter of the outlet of the nozzle is N_{ID} and a length of the extension portion is N_L, and a ratio of N_L to N_{ID} is greater than or equal 0 and less than 1.

According to at least one example embodiment, a printing apparatus comprises: a pressure chamber; a nozzle substrate including a first surface and a second surface opposite to the first surface; and a nozzle including an outlet through which ink contained in the pressure chamber is ejected, the nozzle having a tapered shape in which a size of a cross-sectional area of the nozzle is gradually reduced toward the second surface from the first surface of the nozzle substrate up to the outlet.

According to at least one example embodiment, the printing apparatus further comprises: a trench formed around the nozzle of the nozzle substrate and depressed toward the first surface from the second surface; and a nozzle wall forming a boundary between the nozzle and the nozzle substrate, the nozzle wall extending into the trench.

According to at least one example embodiment, the nozzle has a polypyramid shape.

According to at least one example embodiment, an outer diameter of the outlet of the nozzle is N_{OD} and a depth of the trench is T_D, and a ratio of T_D to N_{OD} is greater than 1

According to at least one example embodiment, the outer diameter and an inner diameter of the outlet of the nozzle are N_{OD} and N_{ID}, respectively, and a ratio of N_{OD} to N_{ID} is less than 5.

According to at least one example embodiment, a method of forming a nozzle of an inkjet apparatus includes: forming a patterned mask layer on a substrate, the patterned mask layer exposing a portion of the substrate; etching the exposed portion of the substrate to form a depression in the substrate; forming a protection layer in the depression; etching the substrate to expose a peak of the protection layer in the depression; removing the protection layer; forming a nozzle wall layer in the depression to form a nozzle; and etching the substrate to form a trench around the nozzle.

According to at least one example embodiment, the mask layer has a <100> crystal orientation and the substrate has a <111> crystal orientation.

According to at least one example embodiment, the protection layer is silicon dioxide.

According to at least one example embodiment, the nozzle wall layer includes at least one of SiN, SiO_2, Ti, Pt, and Ni.

According to at least one example embodiment, at least one of a trench depth and an outer diameter of the nozzle are varied according to a desired magnitude of an electric field to be applied to ink contained in the nozzle during an operation that ejects ink from the nozzle.

According to at least one example embodiment, a width of the trench is varied according to a desired magnitude of an electric field to be applied ink contained in the nozzle during an operation that ejects ink from the nozzle.

According to at least one example embodiment, at least one of an inner diameter, an outer diameter, and a length of the nozzle are varied according to a desired pressure drop occurring in the nozzle during an operation that ejects ink from the nozzle.

According to at least one example embodiment, an outlet of the nozzle extends beyond a lower surface of the substrate.

According to at least one example embodiment, a printing system includes: a printing apparatus, including, a flow channel plate having a nozzle and a trench, the nozzle and an outlet of the nozzle extending into the trench, a piezoelectric actuator configured to apply a piezoelectric force to ink in the nozzle, an electrostatic actuator configured to apply an electrostatic force to the ink in the nozzle; a driving circuit configured to manipulate an application order, amplitude, and duration of each of a piezoelectric driving voltage of the piezoelectric actuator and an electrostatic driving voltage of the electrostatic actuator such that a combined effect of the first and second driving voltages results in a plurality of modes for ejecting ink droplets in various sizes and shapes from the nozzle.

According to at least one example embodiment, the driving circuit is configured to: apply the electrostatic driving voltage to the electrostatic actuator so as to exert the electrostatic force on the ink in the nozzle, and apply the piezoelectric driving voltage to the piezoelectric actuator after the application of the electrostatic driving voltage to form a dome-shaped ink meniscus at the outlet of the nozzle and eject ink droplets having a smaller size than the nozzle outlet; and remove the piezoelectric driving voltage before removing the electrostatic driving voltage.

According to at least one example embodiment, the driving circuit is configured to: apply the piezoelectric driving voltage to the piezoelectric actuator so as to exert pressure on the ink in the nozzle; apply the electrostatic driving voltage to the electrostatic actuator after the application of the piezoelectric driving voltage to form a cone-shaped ink meniscus at the outlet of the nozzle and eject ink droplets having a smaller size than the nozzle outlet from a pointed end of the cone-shaped ink meniscus; and remove the piezoelectric driving voltage before removing the electrostatic driving voltage.

According to at least one example embodiment, the driving circuit is configured to: apply the electrostatic driving voltage to the electrostatic actuator so as to exert the electrostatic force on the ink in the nozzle; apply the piezoelectric driving voltage to the piezoelectric actuator after the application of the electrostatic driving voltage to form a syringe-shaped ink meniscus at the outlet of the nozzle and eject ink in the form of an ink stream from a pointed end of the syringe-shaped ink meniscus; and remove the piezoelectric driving voltage after removing the electrostatic driving voltage.

According to at least one example embodiment, a distance of a printing medium from the outlet of the nozzle is varied according to a desired printing pattern.

According to at least one example embodiment, the nozzle has tapered shape.

According to at least one example embodiment, the nozzle is one of a circular shape, a polypyramid shape, a conical shape, a polygonal shape, and a quadrangular pyramid shape.

BRIEF DESCRIPTION OF THE DRAWINGS

These and/or other aspects will become apparent and more readily appreciated from the following description of the embodiments, taken in conjunction with the accompanying drawings of which:

FIG. **1** is a schematic cross-sectional view of a printing apparatus according to at least one example embodiment;

FIGS. **2** through **6** are schematic cross-sectional views of inkjet printing apparatuses that differ with respect to positions of an electrostatic voltage applier and a ground electrode and a shape of a first electrostatic electrode, according to at least one example embodiment;

FIG. **7**A is a view illustrating a part "A" of FIG. **1**;

FIG. **7**B is a view illustrating equipotential lines formed around a nozzle outlet according to at least one example embodiment;

FIG. **7**C illustrates a shape of a nozzle having concave walls according to at least one example embodiment.

FIG. **7**D illustrates conical shape of a nozzle according to at least one example embodiment.

FIG. **7**E illustrates a trench having relative distances that an effect on a magnitude of an electric field, according to at least one example embodiment.

FIGS. **7**F and **7**G illustrate various configurations of a trench according to an example embodiment.

FIG. **8**A through **8**L are views illustrating a method of forming a nozzle having a tapered shape illustrated in FIG. **7**;

FIG. **9** is a graph showing a result of a simulation measuring movement of ink droplets when a composite method of a piezoelectric method and an electrostatic method is used, according to at least one example embodiment;

FIG. **10** is a graph showing a result of a simulation measuring a change in a magnitude of an electrical field according to a ratio of a depth of a trench to an outer diameter of a nozzle outlet, according to at least one example embodiment;

FIG. **11** is a graph showing a result of a simulation measuring a pressure drop in a nozzle according to a ratio of an outer diameter to an inner diameter of a nozzle outlet, according to at least one example embodiment;

FIG. **12** is a cross-sectional view of a nozzle including an linear extension portion according to at least one example embodiment;

FIG. **13** is a graph showing a result of a simulation measuring a pressure drop in a nozzle according to a length of an extension portion of a nozzle according to at least one example embodiment;

FIG. **14** is a graph showing a result of a simulation measuring a pressure drop in a nozzle according to a ratio of a length of an extension portion of a nozzle to an inner diameter of a nozzle outlet according to at least one example embodiment;

FIG. **15** is a view illustrating a process of ejecting ink in a dripping mode according to at least one example embodiment;

FIG. **16** is a graph showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in a dripping mode according to at least one example embodiment;

FIG. **17** is a view illustrating a process of ejecting ink by a cone-jet mode according to at least one example embodiment;

FIG. **18** is a graph showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in a cone-jet mode according to at least one example embodiment;

FIG. **19** is a view illustrating a process of ejecting ink by a spray mode according to at least one example embodiment; and

FIG. **20** is a graph for showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in a spray mode according to at least one example embodiment.

FIG. **21** illustrates a driving circuit for driving an inkjet apparatus, according to at least one example embodiment.

FIG. **22** illustrates a printing system according to an example embodiment.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

Example embodiments will be understood more readily by reference to the following detailed description and the accompanying drawings. Example embodiments may, however, be embodied in many different forms and should not be construed as being limited to those set forth herein. Rather, these example embodiments are provided so that this disclosure will be thorough and complete. Example embodiments should be defined by the appended claims. In at least some example embodiments, well-known device structures and well-known technologies will not be specifically described in order to avoid ambiguous interpretation.

It will be understood that when an element is referred to as being "connected to" or "coupled to" another element, it can be directly on, connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected to" or "directly coupled to" another element, there are no intervening elements present. Like numbers refer to like elements throughout. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

It will be understood that, although the terms first, second, third, etc., may be used herein to describe various elements, components and/or sections, these elements, components and/or sections should not be limited by these terms. These terms are only used to distinguish one element, component or section from another element, component or section. Thus, a first element, component or section discussed below could be termed a second element, component or section without departing from the teachings of example embodiments.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used in this specification, specify the presence of stated components, steps, operations, and/or elements, but do not preclude the presence or addition of one or more other components, steps, operations, elements, and/or groups thereof.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which example embodiments belong. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Spatially relative terms, such as "below", "beneath", "lower", "above", "upper", and the like, may be used herein for ease of description to describe the relationship of one element or feature to another element(s) or feature(s) as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation, in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as "below" or "beneath" other elements or features would then be oriented "above" the other elements or features. Thus, the exemplary term "below" can encompass both an orientation of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

The present application is related to the co-pending and commonly-assigned U.S. Ser. No. 13/477,383 application entitled, "INKJET APPARATUS AND METHOD OF FORMING NOZZLES", which was invented by Sung-gyu Kang et al. and filed on May 22, 2012, by Samsung Electronics Co., Ltd., and claims the benefit of Korean Patent Application No. 10-2011-0124391, which was filed on Nov. 25, 2011, by Samsung Electronics Co., Ltd. The above application is incorporated herein in its entirety by reference.

FIG. **1** is a cross-sectional view of a printing apparatus according to an example embodiment. Referring to FIG. **1**, the printing apparatus includes a flow channel plate **110**, and a piezoelectric actuator **130** and an electrostatic actuator **140** that respectively provide pressure and an electrostatic driving force for ejecting ink. FIG. **1** illustrates a composite-type inkjet printing apparatus using piezoelectric and electrostatic methods. However, a structure of a nozzle and a trench that will be described later may be used in a piezoelectric-type inkjet printing apparatus or an electrostatic-type inkjet printing apparatus.

An ink channel and a plurality of nozzles **128** for ejecting ink droplets are formed in the flow channel plate **110**. The ink channel may include a plurality of ink inlets **121** through which ink enters and a plurality of pressure chambers **125** for accommodating the entered ink. The ink inlets **121** may be formed at an upper side of the flow channel plate **110** and may be connected to an ink tank (not shown). Ink supplied from the ink tank enters the flow channel plate **110** via the ink inlets **121**. The plurality of pressure chambers **125** are formed in the flow channel plate **110**, and ink entered through the ink inlets **121** is stored in the pressure chambers **125**. Manifolds **122** and **123** and a restrictor **124** may be formed in the flow channel plate **110**. The manifolds **122** and **123** connect the ink inlets **121** and the pressure chambers **125**. The plurality of nozzles **128** are respectively connected to the pressure chambers **125**. Ink stored in the pressure chambers **125** is ejected in the form of droplets through the nozzles **128**. The nozzles **128** may be formed at a lower side of the flow channel plate **110** in a single row or in two or more rows. A plurality of dampers **126** for respectively connecting the pressure chambers **125** and the nozzles **128** to each other may be formed in the flow channel plate **110**.

The flow channel plate **110** may be a substrate formed of a material having suitable micromachining properties, such as a silicon substrate. For example, the flow channel plate **110** may include a channel forming substrate in which the ink channel is formed and a nozzle substrate **111** in which the nozzles **128** are formed. The channel forming substrate may include first and second channel forming substrates **113** and **112**. The ink inlets **121** may be formed to penetrate the first channel forming substrate **113** disposed at an uppermost side of the flow channel plate **110**, and the pressure chambers **125** may be formed in the first channel forming substrate **113** so as to have a desired (or alternatively, predetermined) depth from a bottom surface of the first channel forming substrate **113**. The nozzles **128** may be formed to penetrate a substrate disposed at a lowermost side of the flow channel plate **110**, that is, the nozzle substrate **111**. The manifolds **122** and **123** may be respectively formed in the first channel forming substrate **113** and the second channel forming substrate **112**. The dampers **126** may be formed to penetrate the second channel forming substrate **112**. The three substrates sequentially stacked, that is, the first and second channel forming substrates **113** and **112** and the nozzle substrate **111**, may be bonded to each other by silicon direct bonding (SDB).

As described above, the flow channel plate **110** includes the three substrates **111**, **112**, and **113**, but example embodiments are not limited thereto. The flow channel plate **110** may include one, two, four, or more substrates, and the ink channel formed in the flow channel plate **110** may be disposed in various ways.

The piezoelectric actuator **130** provides a piezoelectric driving force for ejecting ink, that is, a change in pressure, to the pressure chambers **125**. The piezoelectric actuator **130** is formed on the flow channel plate **110** to correspond to the pressure chambers **125**. The piezoelectric actuator **130** may include a lower electrode **131**, a piezoelectric layer **132**, and an upper electrode **133** that are sequentially stacked on the flow channel plate **110**. The lower electrode **131** may serve as a common electrode, and the upper electrode **133** may serve as a driving electrode for applying a voltage to the piezoelectric layer **132**. A piezoelectric voltage applier **135** applies a piezoelectric driving voltage to the lower electrode **131** and the upper electrode **133**. The piezoelectric layer **132** is deformed by the piezoelectric driving voltage applied by the piezoelectric voltage applier **135** to deform the first channel forming substrate **113** constituting an upper wall of the pressure chambers **125**. The piezoelectric layer **132** may be formed of a desired (or alternatively) predetermined piezoelectric material, for example, a lead zirconate titanate (PZT) ceramic material.

The electrostatic actuator **140** may provide an electrostatic driving force to ink contained in the nozzles **128**, and may include a first electrostatic electrode **141** and a second electrostatic electrode **142** that face each other. An electrostatic voltage applier **145** applies an electrostatic voltage between the first electrostatic electrode **141** and the second electrostatic electrode **142**.

For example, the first electrostatic electrode **141** may be disposed on the flow channel plate **110**. The first electrostatic electrode **141** may be formed on an upper surface of the flow channel plate **110**, that is, on an upper surface of the third substrate **113**. In this case, the first electrostatic electrode **141** may be formed on a portion of the flow channel plate **110** in which the ink inlets **121** are formed so as to be spaced apart from the lower electrode **131** of the piezoelectric actuator **130**. The second electrostatic electrode **142** may be disposed so as to be spaced apart from a lower surface of the flow channel plate **110**. A printing medium P on which ink droplets ejected from the nozzles **128** of the flow channel plate **110** are printed is positioned on the second electrostatic electrode **142**.

The electrostatic voltage applier **145** may apply a pulse-type electrostatic driving voltage. In FIG. **1**, the second electrostatic electrode **142** is grounded, but the first electrostatic electrode **141** may be grounded as illustrated in FIG. **2**.

As illustrated in FIGS. **3** and **4**, the electrostatic voltage applier **145** may apply a direct current (DC) voltage type electrostatic driving voltage. In this case, the first electrostatic electrode **141** or the second electrostatic electrode **142** may be grounded.

The position of the first electrostatic electrode **141** is not limited to that illustrated in FIGS. **1** to **4**. As illustrated in FIG. **5**, the first electrostatic electrode **141** may be formed in the flow channel plate **110**. The first electrostatic electrode **141** may be formed on bottom surfaces of the pressure chambers **125**, the restrictor **124**, and the manifold **123**. However, example embodiments are not limited thereto, and the first electrostatic electrode **141** may be formed in any position of the flow channel plate **110**. For example, the first electrostatic electrode **141** may be formed only on the bottom surfaces of the pressure chambers **125**, or alternatively, may be formed on the bottom surface of the restrictor **124** or the manifold **123**. As illustrated in FIG. **6**, the first electrostatic electrode **141** may also be integrally formed with the lower electrode **131**.

FIG. **7**A is a view illustrating a part "A" of FIG. **1**. Referring to FIG. **7**A, the nozzles **128** are formed to penetrate the nozzle substrate **111**. The nozzles **128** have a tapered shape in which a size of a cross-sectional area thereof is reduced toward the lower surface of the flow channel plate **110**, that is, a lower surface **111***a* of the nozzle substrate **111**. Also, a trench **160** is formed around the nozzles **128** so as to be depressed from the lower surface of the flow channel plate **110**, that is, the lower surface **111***a* of the nozzle substrate **111**. A nozzle wall **128***a* forms an outer wall of the nozzles **128**. The nozzle wall **128***a* forms a boundary between the flow channel plate **110** and the nozzles **128**, in detail, between the nozzle substrate **111** and the nozzles **128**. The nozzle wall **128***a* is formed to extend into the trench **160** from the nozzle substrate **111**, and thus the nozzles **128** may have a tapered shape in which an outlet **128***c* extends into the trench **160** toward the lower surface **111***a*.

A trench surface **111***b* formed to differ in level from the lower surface **111***a* is formed in the nozzle substrate **111**. The nozzles **128** are formed in a tapered form to penetrate the nozzle substrate **111** from an upper surface **111***c* of the nozzle substrate **111** to the trench surface **111***b*. The nozzle wall **128***a* forms a boundary between the nozzle substrate **111** and the nozzles **128** and extends toward the lower surface **111***a* to pass through the trench surface **111***b*. An end **128***b* of the nozzle wall **128***a* and an outlet **128***c* may be formed to not cross the lower surface **111***a* of the nozzle substrate **111**. Alternatively, the end **128***b* of the nozzle wall **128***a* and the outlet **128***c* may be formed to cross the lower surface **111***a* of the nozzle substrate **111**.

The nozzles **128** may have a circular shape or a polypyramid shape, and in this regard, a cross-section of the nozzles **128** may have a conical shape (FIG. **7**D) or a polygonal shape. As will be described later, the nozzles **128** may be formed to have a quadrangular pyramid shape by performing anisotropic etching on a single crystal silicon substrate. When a cross-section of the nozzles **128** has a polygonal shape, a diameter of the nozzles **128** may be shown as an equivalent diameter of a circle. Further, as illustrated in FIG. **7**C, the exterior of the nozzles **128** may have concave nozzle walls **128***a*.

The nozzle wall **128***a* may be formed of a material that is different from that for forming the nozzle substrate **111**, for example, one material selected from the group consisting of SiO_2, SiN, Ti, Pt, and Ni. Alternatively, the nozzle wall **128***a* may be formed of a material that is the same as that for forming the nozzle substrate **111**, for example, Si.

FIG. **7**E illustrates nozzles **128** and three relative distances d1, d2, and d3. Distance d1 represents a distance between a center of the nozzle outlet **128***c* and a first location **170**. Distance d2 represents a distance between the first location **170** and a second location **171**. Distance d3 represents a distance between the second location **171** and a third location **172**. A width W of the trench **160** refers to a distance between a center of the nozzle outlet **128***c* and the third location **172**.

According to at least one example embodiment distances d1, d2, and d3 may be varied according to a desired magnitude of an electric field. For example, as distance d1 increases, the magnitude of an electric field decreases. Further, as distances d2 and d3 increase, the magnitude of an electric field increases. Thus, according to an example embodiment, the nozzles **128** and trench **160** may be formed such that the equipotential lines of FIG. **7**B vary according to distances d1, d2, and d3, and/or a width W of the trench **160**.

FIGS. **7**F and **7**G illustrate alternative configurations of the trench **160**, according to at least one example embodiment. In FIG. **7**A, for example, trench **160** forms an obtuse angle (i.e., $\theta>90°$) with the trench surface **111***b*. However, example embodiments are not limited thereto. FIG. **7**F, for example, shows the trench **160** forming a right angle (i.e., $\theta=90°$) with the trench surface **111***b*. According to at least one other example embodiment, FIG. **7**G shows the trench **160** forming an acute angle (i.e., $\theta<90°$) with the trench surface **111***b*.

Hereinafter, a method of forming the nozzles **128** will be described with reference to FIGS. **8**A to **8**L.

An etch mask is formed on a surface of a substrate **210**. For example, referring to FIG. **8**A, the substrate **210**, in which a crystal orientation of an upper surface is an orientation <100>, is prepared, wherein the substrate **210** may be a single crystal silicon substrate. Then, a mask layer **221** is formed. The mask layer **221** may be, for example, a SiO_2 layer. The SiO_2 layer may be formed by oxidizing the substrate **210**. A thickness of the SiO_2 layer may be in a range of, for example, about 100 to about 4000 Å. A photoresist layer **222** is formed on the mask layer **221**, and then the photoresist layer **222** is patterned to partially expose the mask layer **221**. The mask layer **221** is patterned by using the photoresist layer **222** as a mask, thereby forming the substrate **210** in which the mask layer **221** exposing a portion **223** where the nozzles **128** are to be formed is formed, as illustrated in FIG. **8**B. A process of patterning the mask layer **221** may be performed through a wet etching process using an HF solution (a buffered hydrogen fluoride acid).

The substrate **210** is etched by using the mask layer **221** as an etch mask. The etching process may be performed by anisotropic etching using, for example, tetramethyl ammonium hydroxide (TMAH). Referring to FIG. **8**C, the crystal orientation of the upper surface of the substrate **210** is an orientation <100>, and a crystal orientation of an etched surface is an orientation <111>. Due to a difference in etching rates between the orientation <100> and the orientation <111>, the etching is performed rapidly downward and slowly sideward as illustrated in FIGS. **8**C and **8**D. Thus, a depressed portion **230** is formed in the substrate **210** to have a tapered shape in which a cross-sectional area thereof decreases downward. The depressed portion **230** may be formed to have a polypyramid shape or a conical shape by varying a shape of the exposed portion **223** of the mask layer **221**. According to an example embodiment, the exposed portion **223** of the mask layer **221** has a quadrangular shape, thereby forming the depressed portion **230** having a quadrangular pyramid shape. It is not necessary that the depressed portion **230** be formed to pass through a lower surface of the substrate **210**.

A process to penetrate the depressed portion **230** through the lower surface of the substrate **210** is performed. As illustrated in FIG. **8**E, the mask layer **221** formed on the upper and lower surfaces of the substrate **210** is removed by etching, polishing, or the like. Then, as illustrated in FIG. **8**I, the lower surface of the substrate **210** may be polished in order for the depressed portion **230** to pass through the lower surface of the substrate **210**. Also, as illustrated in FIG. **8**F, a protection layer **224** is formed at least on the upper surface of the substrate **210** and on wall surfaces of the depressed portions **230**. The protection layer **224** may be, for example, a SiO_2 layer obtained by oxidizing the substrate **210**. A thickness of the protection layer **224** may be in a range of, for example, about 100 to about 10000 Å. The SiO_2 layer may be spontaneously and unnecessarily formed during an oxidization process on the lower surface of the substrate **210**. Then, the lower surface of the substrate **210** is etched by a desired (or alternatively, predetermined) thickness, for example, through a polishing process as illustrated in FIG. **8**G, and the substrate **210** is etched from the lower surface such that a lower surface **211** of the substrate **210** after being etched is positioned at least above a peak portion **225** of the protection layer **224** formed in the depressed portion **230**. The protection layer **224** protects the depressed portion **230** against an etchant used during an etching process. Then, the protection layer **224** is removed so that the depressed portion **230** passes through the lower surface **211** of the substrate **210** as illustrated in FIG. **8**I.

Next, the nozzle wall **128***a* which forms a boundary between the nozzles **128** and the substrate **210** and the trench **160** are formed. As illustrated in FIG. **8**J, a wall forming material layer **240** is formed on the upper and lower surfaces of the substrate **210** and on the wall surfaces of the depressed portion **230**. The wall forming material layer **240** may be, for example, a SiO_2 layer. In this case, the wall forming material layer **240** may be formed by oxidizing the substrate **210**. Alternatively, the wall forming material layer **240** may be formed by coating, spreading, or depositing SiN, Ti, Pt, Ni, or the like. A thickness of the wall forming material layer **240** may be in a range of, for example, about 100 to about 10000 Å.

Next, as illustrated in FIG. **8**K, a part **241** of the wall forming material layer **240** formed on the lower surface of the substrate **210** is removed. The removing of the part **241** may be performed by coating a photoresist on the wall forming material layer **240**, patterning an area of the photoresist corresponding to the part **241** of the wall forming material layer **240**, and then etching the wall forming material layer **240** by using the patterned photoresist as a mask. As illustrated in FIG. **8**L, the trench **160** is formed by etching the substrate **210** from the lower surface of the substrate **210** by using the remaining wall forming material layer **240** as an etch mask. Thus, the wall forming material layer **240** on the wall surfaces of the depressed portion **230** forms the nozzle wall **128***a*, and the outlet **128***c* is formed to extend into the trench **160**. As illustrated in FIG. **8**L, the outlet **128***c* may be positioned at the same level as the lower surface **111***a*, or alternatively, may be positioned between the lower surface **111***a* and the upper surface **111***c* or may extend below the lower surface **111***a*.

By performing the above-described process, as illustrated in FIG. **7**A, the nozzles **128** are formed in the nozzle substrate **111** to have a tapered shape in which a cross-sectional area thereof decreases toward the lower surface **111***a* of the nozzle substrate **111**, the nozzle wall **128***a* forming a boundary between the nozzle substrate **111** and the nozzles **128** is formed, and the trenches **160** are formed around the nozzles **128** and depressed from the lower surface **111***a* of the nozzle substrate **111**.

Referring to FIG. **7**A, the trench **160** is formed around the tapered nozzles **128**, thereby forming the nozzles **128** having a tapered shape. In general, charges tend to collect on a pointed portion. Also, as illustrated in FIG. **7**B, equipotential lines formed due to an electrostatic driving voltage converge around the outlet **128***c* of the nozzles **128** due to the trench **160**, and thus a relatively large electric field is formed around the outlet **128***c* of the nozzles **128**, thereby increasing an electrostatic driving force at the outlet **128***c* of the nozzles **128**. Accordingly, ink droplets may be effectively accelerated, and a size of the ink droplets may be further reduced according to a magnitude of an applied electrostatic driving voltage. Also, ultra-micro ink droplets with a volume of several picoliters, and furthermore, ultra-micro ink droplets with a volume of several femtoliters, may be stably ejected onto the printing medium P.

FIG. **9** is a graph showing results of a simulation for measuring movement of ink droplets when the ink droplets each about 0.8 femtoliters are ejected from the nozzles **128** each having a quadrangular pyramid shape in which a trench has a depth of 15 μm and the outlet **128***c* has dimensions of 3.15 μm×2.31 μm. An initial speed in which the ink droplets are ejected from the outlet **128***c* of the nozzles **128** is about 3.0 m/s. The printing medium P is spaced apart about 500 μm from the outlet **128***c* of the nozzles **128**. Referring to FIG. **9**, the speed of the ink droplets after about 300 μs approaches 0 due to air resistance when an electrostatic driving voltage is not applied and the ink droplets are ejected only by using a piezoelectric driving force provided by the piezoelectric actuator **130**, and thus the ink droplets do not reach the printing medium P and the ink droplets are scattered. However, when an electrostatic driving voltage of about 2.0 kV is applied, the ink droplets are accelerated due to an electrostatic driving force. Thus, after about 100 μs has elapsed, the ink droplets reach the printing medium P, which is spaced apart about 500 μm from the outlet **128***c* of the nozzles **128**. At this time, the speed of the ink droplets is about 7.0 m/s.

As such, since the printing apparatus according to at least one example embodiment uses both a piezoelectric driving method and an electrostatic driving method, ink may be ejected through a drop-on-demand (DOD) method, and thus it is easy to control a printing operation. Also, a cross-sectional area of the nozzles **128** decreases toward the outlet **128***c*, and the trench **160** is formed around the nozzles **128**, and thus the nozzles **128** may be formed to have a tapered shape. Accordingly, ultra-micro ink droplets may be easily formed, and straightness of the ejected ink droplets may be increased, and thus precision printing may be achieved.

With respect to an outer diameter NOD of the outlet **128***c* of the nozzles **128**, the deeper the trench **160** is, the further the equipotential lines converge around the outlet **128***c* of the nozzles **128**. A depth TD of the trench **160** may be set to satisfy Equation 1 below.

$$\frac{T_D}{N_{OD}} > 1 \tag{1}$$

According to Equation 1, the depth TD of the trench **160** is set to be at least greater than the outer diameter NOD of the outlet **128***c* of the nozzles **128** so that the nozzles **128** may be formed to have a tapered shape, thereby increasing a magnitude of an electric field. As described above, when a cross-section of the nozzles **128** is not circular, an outer diameter and an inner diameter of the nozzles **128** may be calculated assuming that the nozzles **128** are an equivalent circle.

FIG. **10** is a graph showing results of a simulation measuring a change in a magnitude of an electrical field formed around the outlet **128***c* of the nozzles **128** when the trench **160** is not formed and when the trench **160** is formed. In FIG. **10**, a horizontal axis represents a depth ratio TD/NOD of the trench **160**, and a vertical axis represents a ratio EWT/EWOT of a magnitude EWT of the electric field when the trench **160** is formed to a magnitude EWOT of the electric field when the trench **160** is not formed. In FIG. **10**, the smaller a diameter of the nozzles **128** is and the greater the depth ratio TD/NOD of the trench **160** is, the greater a magnitude of the electric field is.

Also, the outlet **128***c* of the nozzles **128** may be formed to be as pointed as possible. For this, the outer diameter NOD of the outlet **128***c* of the nozzles **128** may be formed to be as small as possible, but in this case, the inner diameter NID of the outlet **128***c* of the nozzles **128** is decreased, and thus a pressure drop in the nozzles **128** is increased. Pressure formed in the pressure chambers **125** to eject ink is proportional to a size of a piezoelectric driving voltage, and the piezoelectric driving voltage may be determined to compensate the pressure drop and to eject the ink at a desired (or alternatively, predetermined) speed. In order to eject minute ink droplets, as the inner diameter NID of the outlet **128***c* of the nozzles **128** is decreased, the pressure drop is rapidly increased, and thus a relatively great load is to be applied to the piezoelectric actuator **130**. FIG. **11** is a graph showing a result of a simulation measuring a relationship between a ratio NOD/NID of the outer diameter NOD of the outlet **128***c* of the nozzles **128** to the inner diameter NID of the outlet **128***c* of the nozzles **128** and the pressure drop. As illustrated in FIG. **11**, as the ratio NOD/NID is increased with respect to a given outer diameter NOD, the pressure drop is rapidly increased, and as the inner diameter NID of the outlet **128***c* of the nozzles **128** is decreased, the pressure drop is rapidly increased. The ratio NOD/NID may be set to satisfy Equation 2 below to allow a load to not be excessively applied to the piezoelectric actuator **130** by maintaining the pressure drop below a desired level.

$$\frac{N_{OD}}{N_{ID}} < 5 \quad (2)$$

By setting the ratio NOD/NID to satisfy Equation 2, the pressure drop may be maintained below a desired level up to the outlet **128***c* of the nozzles **128**.

A shape of the nozzles **128** may be determined to minimize the pressure drop in the nozzles **128**. When the nozzles **128** are formed to have a completely tapered shape from an inlet of the nozzles **128** to the outlet **128***c* of the nozzles **128**, that is, when a length of an extension portion **302** (see FIG. **12**) is "0", the pressure drop has a minimum value. However, because of manufacturing errors, as illustrated in FIG. **12**, the nozzles **128** may include the extension portion **302** extending directly downwards from a tapered portion **301**. As illustrated in FIGS. **13** and **14**, the pressure drop occurring in the nozzles **128** is increased as a depth NL of the extension portion **302** is increased and as the inner diameter NID of the outlet **128***c* of the nozzles **128** is decreased. FIG. **14** is a graph for showing a simulation for measuring a relationship between a ratio NL/NID of the length NL of the extension portion **302** to the inner diameter NID of the outlet **128***c* of the nozzles **128** and a pressure drop, wherein the relationship is measured under a condition in which viscosity of ink is 5 cp and an average speed of ink droplets ejected from the outlet **128***c* of the nozzles **128** is maintained at 1 m/s. Thus, it may be seen from FIG. **14** that the pressure drop is increased as the ratio NL/NID is increased. In order to eject minute ink droplets, the inner diameter NID of the outlet **128***c* of the nozzles **128** may be small. However, in this case, as the length NL of the extension portion **302** is increased, the pressure drop is rapidly increased, and thus a relatively great load is applied to the piezoelectric actuator **130**. Accordingly, in order to not excessively increase a piezoelectric driving voltage when the inner diameter NID of the outlet **128***c* of the nozzles **128** is decreased, the length NL of the extension portion **302** needs to be appropriately set. According to the simulation, when the nozzles **128** are formed to satisfy Equation 3 below, an excessive increase in the piezoelectric driving voltage with respect to the inner diameter NID of the outlet **128***c* of the nozzles **128** may be mitigated (or alternatively, prevented).

$$O \leq \frac{N_L}{N_{ID}} < 1 \quad (3)$$

In the printing apparatus according to at least one example embodiment, by controlling an applying order, magnitudes, and durations of a piezoelectric driving voltage applied to the piezoelectric actuator **130** and an electrostatic driving voltage applied to the electrostatic actuator **140**, the printing apparatus may be driven in any of various driving modes for ejecting different sizes and forms of ink droplets. For example, the printing apparatus according to at least one example embodiment may be driven in a dripping mode for ejecting minute ink droplets having a size smaller than that of a nozzle, in a cone-jet mode for ejecting minute ink droplets having a size further smaller than that of droplets ejected in the dripping mode, or in a spray mode for ejecting ink droplets in the form of a jet stream. Hereinafter, the above-described three driving modes will be described.

FIG. **15** is a schematic view describing a dripping mode, and FIG. **16** is a graph showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in the dripping mode illustrated in FIG. **15**.

Referring to FIGS. **15** and **16**, a first operation shows an initial state where a driving voltage is not applied to the piezoelectric actuator **130** and the electrostatic actuator **140**. In this regard, ink **129** contained in the nozzles **128** has a concave shape or a flat meniscus M due to surface tension.

In a second operation, a first electrostatic driving voltage Ve**1** is applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** from the electrostatic voltage applier **145**. The first electrostatic driving voltage Ve**1** may be in a range of, for example, about 3 to about 5 kV. Thus, an electrostatic force is applied to the ink **129** contained in the nozzles **128**, thereby deforming the meniscus M of the ink **129**. As such, when the meniscus M is formed convex, an electric field is converged on the convex meniscus M, and thus positive charges included in the ink **129** move toward the second electrostatic electrode **142** to be converged on the outlet **128***c* of the nozzles **128**.

In a third operation, after the first electrostatic driving voltage Ve**1** is applied between the first electrostatic electrode **141** and the second electrostatic electrode **142**, a desired (or alternatively, predetermined) first piezoelectric driving voltage Vp**1** is applied to the piezoelectric actuator **130** to deform the piezoelectric actuator **130** in a direction in which a volume of the pressure chambers **125** is reduced. The first piezoelectric driving voltage Vp**1** may be in a range of, for example, about 50 to about 90 V, which is higher than a piezoelectric driving voltage applied in a cone-jet mode and a piezoelectric driving voltage applied in a spray mode, which will be described later. The first piezoelectric driving voltage Vp**1** may be properly adjusted according to a size of ink droplets to be ejected. An initial delay time Di taken between when the first electrostatic driving voltage Ve**1** initially peaks to when the first piezoelectric driving voltage Vp**1** initially peaks may be, for example, about 30 μs. A duration time Dp of the first piezoelectric driving voltage Vp**1** may be, for example, about 5 μs.

If the first piezoelectric driving voltage Vp**1** is applied when the first electrostatic driving voltage Ve**1** is applied, the volume of the pressure chambers **125** is reduced, thereby increasing a pressure in the pressure chambers **125**. Accordingly, the meniscus M of the ink **129** contained in the nozzles **128** is made more convex, thereby forming the meniscus M into a dome shape. Thus, a radius of curvature of the meniscus M of the ink **129** is reduced, and more positive charges collect at a convex edge portion of the meniscus M.

In general, an electrostatic force is proportional to an amount of charges and an intensity of an electric field, and an amount of charges is proportional to an intensity of an electric field. Accordingly, an electrostatic force is proportional to a square of the intensity of an electric field. Also, an intensity of an electric field is proportional to an applied electrostatic driving voltage. Since the nozzles **128** has a tapered shape and the trench **160**, equipotential lines converge around the nozzles **128**, and thus an intensity of an electric field formed around the outlet **128***c* of the nozzles **128** is increased. Also, an intensity of an electric field is inversely proportional to the radius of curvature of the meniscus M, and thus an electrostatic force applied to the ink **129** at a protruding portion of the outlet **128***c* of the nozzles **128** is inversely proportional to the square of the radius of curvature of the meniscus M at the protruding portion of the outlet **128***c* of the nozzles **128**. As an electrostatic force applied to the ink **129** at the protruding portion of the outlet **128***c* of the nozzles **128** is increased, the radius of curvature of the meniscus M at a central portion of the nozzles **128** is decreased, and the electrostatic force is further increased. Consequently, the ink **129** at the protruding portion of the outlet **128***c* of the nozzles **128** is separated in the form of ink droplets **129***a* from a surface of the meniscus M. Accordingly, the ink droplets **129***a* having a size smaller than that of the nozzles **128** may be ejected. The separated ink droplets **129***a* are accelerated due to an electrostatic force and move toward the second electrostatic electrode **142** to be printed on the printing medium P. A printing pattern formed of a plurality of ink droplets may be formed on the printing medium P.

Still referring to FIGS. **15** and **16**, the first piezoelectric driving voltage Vp**1** applied to the piezoelectric actuator **130** is removed, and then the first electrostatic driving voltage Ve**1** applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** is removed after a desired (or alternatively, predetermined) period of time. Thus, the piezoelectric actuator **130** returns to its original state, and the pressure in the pressure chambers **125** returns its original state, and accordingly, the meniscus M having a convex shape returns to its original state, that is, to its state in the above-described first operation.

In this regard, a final delay time Df taken from the removal of the first piezoelectric driving voltage Vp**1** to the removal of the first electrostatic driving voltage Ve**1** may be, for example, about 20 μs. As such, in the dripping mode, the first electrostatic driving voltage Ve**1** is applied earlier and is removed later than the first piezoelectric driving voltage Vp**1**, and thus, a duration time De of the first electrostatic driving voltage Ve**1** is longer than the duration time Dp of the first piezoelectric driving voltage Vp**1**.

According to the dripping mode, ink droplets having a size smaller than that of a nozzle may be ejected. That is, ink droplets with a volume of about several picoliters or ultra-micro ink droplets with a volume of several femtoliters may be ejected via a nozzle having a relatively large diameter, for example, a diameter in a range of several to several tens of μm. Also, minute ink droplets may be ejected by using a nozzle having a relatively large diameter, and thus a possibility that the nozzle is clogged is decreased, thereby increasing reliability of the printing apparatus.

FIG. **17** is a schematic view for describing a cone-jet mode, and FIG. **18** is a graph for showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in the cone-jet mode illustrated in FIG. **17**.

Referring to FIGS. **17** and **18**, a first operation shows an initial state where a driving voltage is not applied to the piezoelectric actuator **130** and the electrostatic actuator **140**, and the ink **129** contained in the nozzles **128** has a slightly concave shape or a flat meniscus M due to surface tension.

In a second operation, a desired (or alternatively, predetermined) second piezoelectric driving voltage Vp**2** is applied to the piezoelectric actuator **130** to deform the piezoelectric actuator **130** in a direction in which the volume of the pressure chambers **125** is reduced. The second piezoelectric driving voltage Vp**2** is in a range of, for example, about 25 to about 40 V, which is lower than the first piezoelectric driving voltage Vp**1** in the dripping mode and is higher than a piezoelectric driving voltage in a spray mode to be described later. A duration time Dp of the second piezoelectric driving voltage Vp**2** is, for example, about 22 μs, which is longer than that of the first piezoelectric driving voltage Vp**1** in the dripping mode. The volume of the pressure chambers **125** is decreased, and thus the pressure of the pressure chambers **125** is increased, thereby deforming the meniscus M of the ink **129** contained in the nozzles **128** so as to have a convex shape.

In a third operation, after the second piezoelectric driving voltage Vp**2** is applied, a second electrostatic driving voltage Ve**2** is applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** from the electrostatic voltage applier **145**. The second electrostatic driving voltage Ve**2** may be, for example, about 3 to about 5 kV. An initial duration time Di taken from when the second piezoelectric driving voltage Vp**2** initially peaks to when the second electrostatic driving voltage Ve**2** initially peaks may be, for example, about 9 μs.

When the second electrostatic driving voltage Ve**2** is applied, an electric field converges on a protruding portion of the ink **129**, and thus positive charges included in the ink **129** move toward the electrostatic electrode **142** and collect at the outlet **128***c* of the nozzles **128**, thereby increasing an electrostatic force applied to the protruding portion of the ink **129**. When an electrical conductivity of the ink **129** is relatively low and when a viscosity of the ink **129** is relatively high, the meniscus M of the ink **129** may be deformed into a Taylor cone shape. The ink **129** at the protruding portion having a Taylor cone shape is separated from the ink **129** contained in the nozzles **128** in the form of ink droplets **129***a*. Since the ink droplets **129***a* are separated from a pointed edge portion of the meniscus M having a Taylor cone shape, a size of the ink droplets **129***a* may be smaller than that of ink droplets in the dripping mode. The separated ink droplets **129***a* move toward the second electrostatic electrode **142** due to an electrostatic force to be printed on the printing medium P. A printing pattern formed of a plurality of ink droplets may be formed on the printing medium P.

Still referring to FIGS. **17** and **18**, the second piezoelectric driving voltage Vp**2** applied to the piezoelectric actuator **130** is removed, and after a desired or (alternatively, predetermined) period of time has elapsed, the second electrostatic driving voltage Ve**2** applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** is removed. Thus, the piezoelectric actuator **130** returns to its original state, and the pressure in the pressure chambers **125** returns its original state, and accordingly, the meniscus M having a Taylor cone shape returns to its original state, that is, to its state in the above-described first operation. A final delay time Df taken from the removal of the second piezoelectric driving voltage Vp**2** to the removal of the second electrostatic driving voltage Ve**2** may be, for example, about 20 μs. As such, in the cone-jet mode, the second piezoelectric driving voltage Vp**2** is applied earlier and is removed earlier than the second electrostatic driving voltage Ve**2**. A duration time De of the second electrostatic driving voltage Ve**2** is longer than the duration time Dp of the second piezoelectric driving voltage Vp**2**.

According to the cone-jet mode, ink droplets having a size smaller than that of the ink droplets in the above-described dripping mode may be ejected. The dripping mode and the cone-jet mode are influenced by an electrical conductivity and a viscosity of ink. For example, in ink having a relatively high electrical conductivity and a relatively low viscosity, a speed of charges traveling toward a surface of the ink is relatively great, and thus ink droplets are easily separated from a meniscus having a dome shape before forming the meniscus to have a Taylor cone shape, thereby easily ejecting the ink droplets in the dripping mode. On the other hand, in ink having a relatively low electrical conductivity and a relatively high viscosity, a speed of charges travelling toward a surface of the ink is relatively low, and thus a meniscus M having a Taylor cone shape may be easily formed, thereby ejecting minute ink droplets in the cone-jet mode. Accordingly, the above-described two modes, that is, the dripping mode and the cone-jet mode, may be realized by properly using a characteristic of ink. For the cone-jet mode, a piezoelectric driving voltage is maintained relatively low so that an electrostatic force for pulling the ink **129** out of the nozzles **128** is greater than a pressure for pushing the ink **129** out of the nozzles **128**, thereby easily forming the meniscus M having a Taylor cone shape.

FIG. **19** is a schematic view describing a spray mode, and FIG. **20** is a graph showing waveforms of a piezoelectric driving voltage and an electrostatic driving voltage used in the spray mode illustrated in FIG. **19**.

Referring to FIGS. **19** and **20**, a first operation shows an initial state where a driving voltage is not applied to the piezoelectric actuator **130** and the electrostatic actuator **140**. In this regard, the ink **129** contained in the nozzles **128** has a slightly concave shape or a flat meniscus M due to surface tension.

In a second operation, a third electrostatic driving voltage Ve**3** is applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** from the electrostatic voltage applier **145**. The third electrostatic driving voltage Ve**3** may be in a range of, for example, about 5 to about 7 kV. Thus, an electrostatic force is applied to the ink **129** contained in the nozzle **129**, thereby deforming the meniscus M of the ink **129** into a slightly convex shape. If the convex meniscus M is formed, an electric field converges on the convex meniscus M, and thus positive charges included in the ink **129** move toward the second electrostatic electrode **142** and collect at the outlet **128***c* of the nozzles **128**.

In a third-1 operation, after a desired (or alternatively, predetermined) period of time has elapsed from the application of the third electrostatic driving voltage Ve**3**, a desired (or alternatively, predetermined) third piezoelectric driving voltage Vp**3** is applied to the piezoelectric actuator **130** to deform the piezoelectric actuator **130** in a direction in which the volume of the pressure chambers **125** is reduced. The third piezoelectric driving voltage Vp**3** may be, for example, about 10 V, which is lower than piezoelectric driving voltages in the above-described dripping mode and the cone-jet mode. An initial delay time Di taken from when the third electrostatic driving voltage Ve**3** initially peaks to when the third piezoelectric driving voltage Vp**3** initially peaks may be, for example, about 18 μs.

If the third piezoelectric driving voltage Vp**3** is applied when the first third electrostatic driving voltage Ve**3** is applied, the volume of the pressure chambers **125** is reduced, and thus the pressure in the pressure chambers **125** is increased, thereby pushing the ink **129** contained in the nozzles **128** out of the nozzles **128**. The third piezoelectric driving voltage Vp**3** is maintained relatively low and the third electrostatic driving voltage Ve**3** is maintained relatively high, and thus an electrostatic force for pulling the ink **129** out of the nozzles **128** is greater than a pressure for pushing the ink **129** out of the nozzles **128**, thereby forming the meniscus M having a Taylor cone shape. Furthermore, when the electrical conductivity of the ink **129** is relatively low and when the viscosity of the ink **129** is relatively high, the meniscus M having a Taylor cone shape may be easily formed. The ink **129** at a protruding portion of the meniscus M having a Taylor cone shape may extend toward the second electrostatic electrode **142** in the form of a stream **129***b* due to an electrostatic force. If the printing medium P is disposed relatively close to the nozzles **128**, the ink stream **129***b* may extend up to the printing medium P. Accordingly, a printing pattern formed of a plurality of ink streams may be formed on the printing medium P.

Referring to a third-2 operation, if the printing medium P is disposed relatively far away from the nozzles **128**, the ink stream **129***b* may not extend up to the printing medium P, and an end of the ink stream **129***b* is divided into ultra-micro ink droplets at a portion close to the printing medium P to be dispersed toward the printing medium P. In this case, a printing pattern coated using a spray method may be formed on at least a part of the printing medium P.

Still referring to FIGS. **19** and **20**, the third electrostatic driving voltage Ve**3** applied between the first electrostatic electrode **141** and the second electrostatic electrode **142** is removed, and after a desired or (alternatively, predetermined) period of time has elapsed, the third piezoelectric driving voltage Vp**3** applied to the piezoelectric actuator **130** is removed. Thus, the piezoelectric actuator **130** returns to its original state, and the pressure in the pressure chambers **125** returns its original state, and accordingly, the meniscus M having a Taylor cone shape returns to its original state, that is, to its state in the above-described first operation.

A final delay time Df taken from the removal of the third electrostatic driving voltage Ve**3** to the removal of the third piezoelectric driving voltage Vp**3** may be, for example, about 5 μs. As such, in the spray mode, the third electrostatic driving voltage Ve**3** is applied earlier and is removed earlier than the third piezoelectric driving voltage Vp**3**. A duration time De of the third electrostatic driving voltage Ve**3** is longer than the duration time Dp of the third piezoelectric driving voltage Vp**3**. Also, the duration time Dp of the third piezoelectric driving voltage Vp**3** may be, for example, about 12 μs, which is longer than the duration time Dp of the first piezoelectric driving voltage Vp**1** of the above-described dripping mode and is shorter than the duration time Dp of the second piezoelectric driving voltage Vp**2** in the above-described cone-jet mode.

As such, according to the spray mode, ink may extend in the form of a stream to form a printing pattern formed of a plurality of solid lines on a printing medium, or an ink stream may be dispersed to form a printing pattern coated using a spray method on a printing medium.

FIG. **21** illustrates a driving circuit **400** of an inkjet printing apparatus according to at least one example embodiment.

Driving circuit **400** may include a controller **440** and a voltage generator **450**. The controller **440** may include, for example, a processor or other device well-known as capable of driving printing apparatuses. According to an example embodiment, the controller **440** may receive a mode select signal MSS, and the mode select signal MSS signal may indicate a particular mode of operation for an inkjet apparatus. According to an example embodiment, the mode select signal MSS may indicate a drip mode, a cone-jet mode, and/or a spray mode as described above with respect to FIGS. **15-20**.

Controller **440** may include a drip signal generator **410**, a cone-jet signal generator **420**, and/or a spray-signal generator **430**. Each of the signal generators **410**, **420**, and **430** may receive the mode selection signal MSS and may output a drip signal, cone-jet signal, and a spray signal as mode signals MS**1**, MS**2**, MS**3** based on the mode selection signal MSS.

The voltage generator **450** may include a piezoelectric voltage source and an electrostatic voltage source. The voltage generator **450** may receive one of mode signals MS**1**, MS**2**, and MS**3** and output a piezoelectric driving voltage V_{PD} and an electrostatic driving signal V_{ED} for driving a printing apparatus in a drip mode, cone-jet mode, and/or a spray mode. Piezoelectric driving voltage V_{PD} and electrostatic driving voltage V_{ED} may have waveforms, amplitudes, and signal delays similar to the piezoelectric driving voltage Vp and electrostatic driving voltage Ve described above with respect to FIGS. **15-20**.

FIG. **22** illustrates a printing system according to at least one example embodiment.

Printing system **500** may include a printing apparatus **510** and a driving circuit **520**. Although the printing apparatus **510** and driving circuit **520** are illustrated as being separate devices, it should be understood that printing apparatus **510** and driving circuit **520** may be integrated into a single device. In FIG. **22**, printing apparatus **510** may be a printing apparatus according one of FIGS. **1-6**. As shown in FIGS. **1-6**, printing apparatus **510** may include a nozzle having a tapered shape. Further, the driving circuit **520** may be the driving circuit illustrated in FIG. **21**.

So far, example embodiments of a composite-type printing apparatus using piezoelectric and electrostatic methods have been described. However, these are just example embodiments, and the above-described structure and manufacturing method of the nozzles or the trench may be used in a piezoelectric-type or electrostatic-type printing apparatus.

It should be understood that example embodiments described herein should be considered in a descriptive sense only and not for purposes of limitation. Descriptions of features or aspects within each example embodiment should typically be considered as available for other similar features or aspects in other example embodiments.

What is claimed is:

1. A printing apparatus comprising:

a flow channel plate including,

a pressure chamber,

a trench recessed from a bottom surface of the flow channel plate, the trench including a trench surface differing in level from the bottom surface;

a nozzle penetrating the flow channel plate, the nozzle including,

a tapered portion of which a size of a cross-sectional area decreases toward the bottom surface,

an outlet at an end of the tapered portion, through which ink contained in the pressure chamber is ejected, and

a nozzle wall defining the tapered portion and the outlet, the nozzle wall having a boundary with the flow channel plate and extending toward the bottom surface beyond the trench surface to the outlet such that an outer surface of the tapered portion is exposed to the trench;

a piezoelectric actuator configured to provide a change in pressure to eject the ink contained in the pressure chamber; and

an electrostatic actuator configured to provide an electrostatic driving force to the ink contained in the nozzle.

2. The printing apparatus of claim **1**, wherein the nozzle has a polypyramid shape.

3. The printing apparatus of claim **1**, wherein the flow channel plate is formed of Si, and the nozzle wall is formed of at least one of SiO_2, SiN, Si, Ti, Pt, and Ni.

4. The printing apparatus of claim **1**, wherein the flow channel plate comprises:

a channel forming substrate in which an ink channel is formed, and

a nozzle substrate in which the nozzle and the trench are formed, the nozzle substrate being joined to the channel forming substrate, and the nozzle substrate being a single crystal silicon substrate.

5. The printing apparatus of claim **4**, wherein the nozzle wall is formed of SiO_2.

6. The printing apparatus of claim **5**, wherein the SiO_2 is formed by oxidizing the nozzle substrate.

7. The printing apparatus of claim **1**, wherein an outer diameter of the outlet of the nozzle is N_{OD} and a depth of the trench is T_D, and a ratio of T_D to N_{OD} is greater than 1.

8. The printing apparatus of claim **1**, wherein the outer diameter and an inner diameter of the outlet of the nozzle are N_{OD} and N_{ID}, respectively, and a ratio of N_{OD} to N_{ID} is less than 5.

9. The printing apparatus of claim **1**, wherein the nozzle comprises:

an extension portion linearly extending from the tapered portion, and an inner diameter of the outlet of the nozzle is N_{ID} and a length of the extension portion is N_L, and a ratio of N_L to N_{ID} is greater than or equal to 0 and less than 1.

10. A printing apparatus comprising:

a channel forming substrate including a pressure chamber;

a nozzle substrate including an upper surface, a lower surface, and a trench surface formed between the upper surface and the lower surface so as to differ in level from the upper and lower surfaces; and

a nozzle penetrating the nozzle substrate from the upper surface toward the lower surface so as to have a tapered shape in which a size of a cross-sectional area of the nozzle is gradually reduced, the nozzle including a nozzle wall that defines the tapered shape and an outlet at an end of the tapered shape through which ink contained in the pressure chamber is ejected, the nozzle wall having a boundary with the nozzle substrate and extending toward the lower surface beyond the trench surface such that an outer surface of the tapered shape is exposed to the trench.

11. The printing apparatus of claim **10**, wherein the nozzle substrate is a single crystal silicon substrate, and the nozzle is formed of SiO_2.

12. The printing apparatus of claim **10**, wherein an outer diameter of the outlet of the nozzle is N_{OD} and a depth of the trench surface from the lower surface is T_D, and a ratio of T_D to N_{OD} is greater than 1.

13. The printing apparatus of claim **12**, wherein the outer diameter and an inner diameter of the outlet of the nozzle are N_{OD} and N_{ID}, respectively, and a ratio of N_{OD} to N_{ID} is less than 5.

14. The printing apparatus of claim **13**, wherein the nozzle comprises:

an extension portion linearly extending downward from a portion having a tapered shape, and the inner diameter of the outlet of the nozzle is N_{ID} and a length of the extension portion is N_L, and a ratio of N_L to N_{ID} is greater than or equal 0 and less than 1.

15. The printing apparatus of claim **1**, wherein the nozzle wall forms a pointed portion at the outlet.

16. The printing apparatus of claim **1**, wherein an inner surface of the tapered portion, opposite to the outer surface, is exposed to the ink.

* * * * *